ORIGINAL ARTICLE AJO-DO

Chin development as a result of differential jaw growth

Steven D. Marshall,[a] Laura E. Low,[b] Nathan E. Holton,[c] Robert G. Franciscus,[d] Mike Frazier,[e] Fang Qian,[f] Kyle Mann,[g] Galen Schneider,[h] Jill E. Scott,[i] and Thomas E. Southard[j]
Iowa City and Des Moines, Iowa, and Indianapolis, Indiana

Introduction: During facial growth, the maxilla and mandible translate downward and forward. Although the forward displacement of the maxilla is less than that of the mandible, the interarch relationship of the teeth in the sagittal view during growth remains essentially unchanged. Interdigitation is thought to provide a compensatory (tooth movement) mechanism for maintaining the pattern of occlusion during growth: the maxillary teeth move anteriorly relative to the maxilla while the mandibular teeth move posteriorly relative to the basilar mandible. The purpose of this study was to investigate the hypothesis that the human chin develops as a result of this process. **Methods:** Twenty-five untreated subjects from the Iowa Facial Growth Study with Class I normal occlusion were randomly selected based on availability of cephalograms at T1 (mean = 8.32 yr) and T2 (mean = 19.90 yr). Measurements of growth (T2 minus T1) parallel to the Frankfort horizontal (FH) for the maxilla, maxillary dentition, mandible, mandibular dentition, and pogonion (Pg) were made. **Results:** Relative to Pg (a stable bony landmark), B-point moved posteriorly, on average 2.34 mm during growth, and bony chin development (B-point to Pg) increased concomitantly. Similarly, the mandibular and maxillary incisors moved posteriorly relative to Pg 2.53 mm and 2.76 mm, respectively. A-point, relative to Pg, moved posteriorly 4.47 mm during growth. **Conclusions:** Bony chin development during facial growth occurs, in part, from differential jaw growth and compensatory dentoalveolar movements. (Am J Orthod Dentofacial Orthop 2011;139:456-64)

The chin, or more specifically the protuberance of the bony mandibular landmark, the mentum osseum, is a facial feature unique to modern humans. Humans differ in the forward projection of the mentum osseum compared with higher primates and other species of *Homo* who lack a similar prominence of this mandibular landmark. Why is this so?

The development of the chin in modern humans has largely been viewed in the literature as an evolutionary change in mandibular architecture brought about by altered function and biomechanical forces as the mandible diminished in size.[1-4] Recent studies, however, have documented that the formation of the human chin cannot be explained entirely as a function of biomechanics.[5,6] In contrast to a purely biomechanical explanation, other studies have suggested that modern human chin morphology is the result of a posterior displacement of the mandibular dentition relative to the basal region of the mandible, and the evolution of the human chin is the result of a relative independence of the alveolar and basilar regions of the mandible.[7-9] This would suggest that the degree of development of the chin is largely a function of the alveolar region of the mandible "drifting back" along the basal region of the mandibular corpus.

It is well established that during facial growth the anterior aspect of the mandibular alveolus at the symphysis is resorptive,[10,11] while the lower symphyseal border, near Pg, is developmentally stable and exhibits little to no remodeling.[12-18] As such, formation of the human chin is not the result of bony deposition along its anterior surface. Chen et al, for example, conducted a longitudinal analysis of the mandibular outline, in

[a] Visiting associate professor, Department of Orthodontics, College of Dentistry, University of Iowa, Iowa City, IA.
[b] Private practice, Hospital dentistry, University of Iowa, Iowa City, IA.
[c] Graduate student, Department of Anthropology, University of Iowa, Iowa City, IA.
[d] Associate professor, Department of Anthropology and Neuroscience Graduate Program, University of Iowa, Iowa City, IA.
[e] Associate clinical professor, Department of Orthodontics, Indiana University School of Dentistry, Indianapolis, IN.
[f] Associate research scientist and adjunct assistant professor, Department of Preventative and Community Dentistry, College of Dentistry, University of Iowa, Iowa City, IA.
[g] Private practice, Des Moines, IA.
[h] Associate professor, Department of Prosthodontics and Dows Institute for Dental Research, The University of Iowa, Iowa City, IA.
[i] Graduate student, Department of Anthropology, University of Iowa, Iowa City, IA.
[j] Professor and head, Department of Orthodontics, College of Dentistry, University of Iowa, Iowa City, IA.

The authors report no commercial, proprietary, or financial interest in the products or companies described in this article.

Reprint requests to: Steven D. Marshall, Department of Orthodontics, College of Dentistry, University of Iowa, Iowa City, IA 52242; e-mail, steven-marshall@uiowa.edu.

Submitted, January 2009; revised and accepted, May 2009.
0889-5406/$36.00

doi:10.1016/j.ajodo.2009.05.038

norma lateralis, using elliptical Fourier analysis.[18] Their data suggest that the prominence of the chin results from the posterior placement of the mandibular incisors relative to the chin rather than from an increase in the relative size of the chin at Pg.

The posterior migration of the mandibular dentition is developmentally linked to the differential growth of the mandible and maxilla. This was originally suggested by Lager.[19] More recently You et al[20] documented that the forward growth of the mandible was, on average, nearly 5 mm more than that of the maxilla in a longitudinal sample. Similarly, while the mandibular dentition moved anteriorly relative to the maxillary basal bone, it migrated posteriorly relative to the mandibular basal bone. The posterior position of the mandibular dentition relative to the basal bone of the mandible is likely due to the interdigitation and function of the mandibular and maxillary dentition in promoting maintenance of the occlusal pattern.[20-22] As the mandible outgrows the maxilla, the mandibular dentition is, in effect, dragged relatively posterior by the maxilla.

The purpose of this study was to assess the longitudinal development of the chin as a function of differential jaw growth and spatial positioning of the mandible, the maxilla, and the dentition. We did this by testing 2 specific hypotheses in a longitudinal sample of untreated subjects.

- Hypothesis 1: The horizontal projection of the chin is a function of differential anterior growth between the mandibular body and the mandibular dentition and its associated alveolar bone; that is, the chin develops as the mandibular dentition exhibits posterior displacement relative to mandibular basilar bone during jaw growth.
- Hypothesis 2: Changes in the anterior-posterior position of the mandibular dentition during growth and development follow concomitant changes in the maxillary dentition as a function of maxillary growth relative to the mandible. As such, variation in the position of the mandibular dentition during growth should follow that of the maxilla.

MATERIAL AND METHODS

To test our hypotheses, material was obtained from the Iowa Facial Growth Study. This pure longitudinal study began with 183 whites (92 males and 91 females). Included in this study are lateral and anterior-posterior cephalograms, as well as intraoral models, taken every 6 months between the ages of 5 and 12 years and annually thereafter through age 18 years. A final set of records was taken at adulthood. All subjects had a normal angle Class I molar and canine relationship and were free of any facial or skeletal disharmony. Subject participation in the growth study diminished with age, leaving 100 participants at age 12 years and 70 participants in early adulthood.

A subset of 25 subjects (13 males and 12 females) who had never received orthodontic treatment or extractions of permanent teeth (third molars excluded) were randomly selected based on the availability of lateral cephalograms with sufficient image quality in the regions of interest at the ages studied. Time point 1 (T1) was during childhood at around 8 years of age (mean = 8.32 years; SD = 0.24 years), while time point 2 (T2) was during early adulthood, with ages ranging from 16 to 28 years (mean = 19.90 years; SD = 3.88 years). Table I provides descriptive statistics and selected skeletal cephalometric relationships for our sample. Although these subjects had normal (Class I) occlusion during growth, they did exhibit considerable variation in skeletal cephalometric measurements.

For the measurements used in our study, on each of the lateral cephalograms the following landmarks were identified (Fig 1):

1. **A-point (A):** the deepest point of the bony concavity of the maxilla between the anterior nasal spine and the prosthion
2. **Maxillary incisor (Mx1):** the anteriormost portion of the maxillary incisal edge
3. **Maxillary first molar (Mx6):** the most anterior point on the mesial surface of the maxillary first molar crown
4. **B-point (B):** the deepest point of the bony concavity of the mandible between the infradentale and Pg
5. **Pg :** the most anterior point on the contour of the bony chin
6. **Mandibular incisor (Mn1):** the anteriormost portion of the mandibular incisal edge
7. **Mandibular first molar (Mn6):** the most anterior point on the mesial surface of the mandibular first molar crown

The lateral cephalograms were traced by hand. For any landmark that did not lie in the midsagittal plane, the midpoint between the right and left points was used. When hand tracing, all cephalometric landmarks were identified using a 0.5-mm mechanical lead pencil. All tracings were verified by a second independent investigator, and discrepancies were resolved by the second investigator. Linear measurements on the tracings were recorded using a stainless steel digital caliper to the nearest tenth of a millimeter and were corrected for enlargement.

The measurements between landmarks are defined in Table II. At T1 and T2, linear measurements to each landmark were made parallel to the FH from a constructed reference line through the sella perpendicular

Table I. Descriptive statistics for gender, age,* and selected skeletal cephalometric measurements†

Subject	*Gender*	*Age T1*	*Age T2*	*ANB angle T1*	*ANB angle T2*	*SN-MP T1*	*SN-MP T2*	*NA-FH T1*	*NA-FH T2*
1	M	8.0	17.0	1.5	−0.5	28.5	29.0	83.5	84.0
2	M	8.0	17.0	4.5	5.0	23.0	17.0	92.0	95.0
3	M	8.5	18.0	2.0	2.0	19.0	11.0	90.0	89.5
4	M	8.0	25.7	6.0	3.0	30.0	23.5	90.0	90.5
5	M	8.0	17.0	2.5	2.0	32.0	27.0	84.0	85.5
6	M	8.5	17.1	2.0	0.5	37.0	36.0	80.0	83.0
7	M	8.0	18.0	2.5	5.0	24.5	20.0	91.0	93.0
8	M	8.5	26.0	2.0	−1.0	24.0	22.0	87.0	86.0
9	M	8.5	25.8	2.0	1.0	30.0	23.0	85.0	90.0
10	M	8.0	22.6	5.0	2.0	40.0	35.0	84.0	86.0
11	M	8.0	23.6	5.0	3.5	28.0	25.0	86.5	93.5
12	M	8.5	22.6	3.0	1.0	35.0	31.0	81.5	80.0
13	M	8.5	22.5	3.0	2.0	33.0	26.5	85.0	89.5
14	F	8.0	18.0	2.5	3.5	29.5	27.5	86.0	87.5
15	F	8.0	28.1	4.0	2.5	31.0	27.0	86.0	86.0
16	F	8.5	17.1	3.0	1.0	21.5	24.0	90.0	90.0
17	F	8.5	18.0	3.0	4.0	32.0	29.5	90.0	92.5
18	F	8.5	18.0	6.5	6.0	35.0	35.0	88.0	88.5
19	F	8.5	17.0	5.0	3.5	40.5	32.5	82.0	89.0
20	F	8.5	16.0	5.5	6.5	28.0	24.0	87.0	91.0
21	F	8.5	17.0	5.0	4.5	38.0	31.5	84.5	88.0
22	F	8.5	16.8	2.5	2.5	34.0	31.0	87.0	87.5
23	F	8.5	17.1	5.5	5.0	33.5	27.0	87.0	89.0
24	F	8.5	16.0	4.0	2.0	32.0	28.0	88.0	87.0
25	F	8.5	25.2	1.5	−1.5	32.0	27.0	84.0	85.0

*In years; †In degrees.

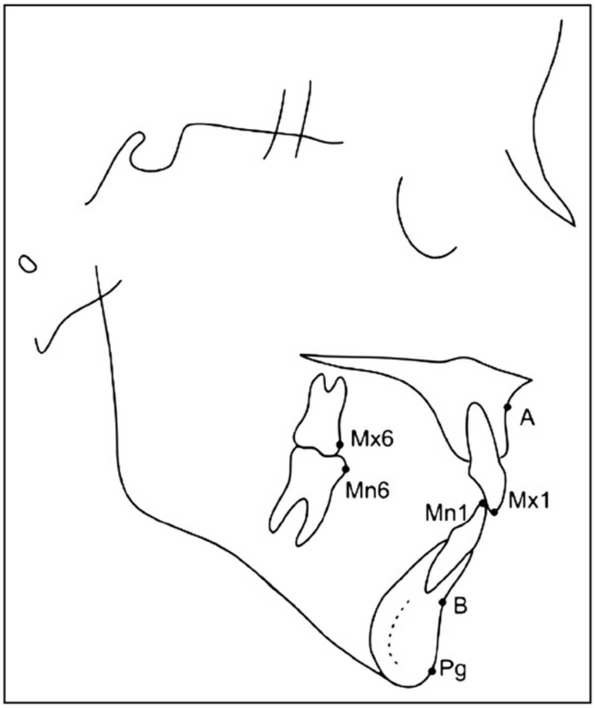

Fig 1. Cephalometric landmarks used to derive measurements.

to the FH. The change in the position of each cephalometric landmark, between T1 and T2 (relative to the constructed reference line and parallel to the FH) was calculated as the difference between linear measurements for each landmark taken at T1 and T2. Given the developmental stability of Pg during growth,[12-18] this T1 to T2 change in each cephalometric landmark was referenced to the amount of T1 to T2 change in the position of Pg. Thus, the measurement "B-Pg" in Table II is the change in linear distance from the reference line to B-point (T2 minus T1) minus the change in linear distance from the reference line to Pg (T2 minus T1). All other measures in Table II were derived similarly by subtracting the T1 to T2 Pg change from the T1 to T2 landmark change.

To determine the ability to accurately replicate the cephalometric measurements, interobserver error was tested by remeasuring a subset (40%) of the sample with at least a 24-hour intervening period. Measurements were taken with a high degree of accuracy, as the average error between observations was less that 1% (SD ± 2.7%).

To test our first hypothesis, we examined the Pearson correlation (r) and coefficient of determination (r^2) between the developmental change in chin size (B-Pg) and the developmental change in mandibular dentition

Table II. Mandibular and maxillary measurements relative to pogonion*

	Definition
Mandibular Measurement	
B-Pg	Chin size
Mn1-Pg	Position of central mandibular incisor relative to Pg
Mn6-Pg	Position of first mandibular molar relative to Pg
Maxillary Measurement	
A-Pg	Position of the maxilla relative to Pg
Mx1-Pg	Position of central maxillary incisor relative to Pg
Mx6-Pg	Position of first maxillary molar relative to Pg

Pg = pogonion.
*All measurements were taken parallel to the Frankfort Horizontal (FH) from a reference line perpendicular to FH and intersecting sella.

position (Mn1-Pg and Mn6-Pg). We would predict a significant positive correlation between chin development and the longitudinal change in the position of the dentition such that greater posterior placement of the dentition is associated with greater chin development. We would further predict that a majority of the variance in the developmental change in B-Pg is explained by variation in the developmental change in the position of the mandibular dentition.

Our second hypothesis was similarly tested by examining r and r^2 between the developmental change in mandibular dentition position (Mn1-Pg and Mn6-Pg) and their maxillary counterparts (Mx1-Pg and Mx6-Pg) as well as the anterior projection of the maxilla relative to Pg (A-Pg). Should the change in the position of the mandibular dentition follow the change in the position of the maxillary dentition, presumably due to the effects of interocclusal tooth contacts during function, we would predict that the developmental change in the mandibular dentition should be significantly positively correlated with Mx1-Pg, Mx6-Pg, and A-Pg. We would, in addition, predict that the majority of the variance in the developmental change in the position of the mandibular dentition should be explained by the change in our maxillary variables.

Mandibular rotation has been shown to occur during facial growth in untreated subjects.[17,23] Given that our measure of chin development is taken relative to the FH, it is potentially sensitive to the variation in mandibular rotation. To assess whether longitudinal change in mandibular plane angle is a confounding factor when measuring longitudinal change in chin size along the FH, we examined the Pearson correlation (r) between the developmental change in chin size and the developmental change in the mandibular plane angle (SN-MP). Should the change in horizontal projection of the chin (relative to B-point) follow the change in mandibular plane angle, we would predict that the developmental change in chin size should be significantly negatively correlated with the developmental change in mandibular plane angle.

To further assess chin development and associated mandibular and maxillary growth, we also used generalized Procrustes analysis[24] (GPA) on a series of 15 coordinate landmarks taken on the lateral cephalograms (Table III, Figure 2) at both T1 and T2. GPA is a geometric morphometric method, using 2D or 3D coordinates of definable landmarks that allow comparison of shapes irrespective of size, location, or rotation of the objects. Principal components analysis on Procrustes scaled landmarks (ie, landmarks scaled for size) was used to assess residual shape differences in maxillary and mandibular growth from the 2 time periods.

RESULTS

Descriptive statistics are presented in Table IV and illustrated in Figure 3. Relative to Pg, B-point moved posteriorly an average of 2.34 mm. Thus, chin development increased from T1 to T2. Similarly the mandibular (Mn1-Pg) and maxillary (Mx1-Pg) incisors moved posteriorly relative to Pg 2.53 mm and 2.76 mm, respectively. A-point, relative to Pg, experienced the greatest degree of relative posterior displacement during growth, with an average value of 4.47 mm of movement. In contrast to all other measurements, both Mn6 and Mx6 migrated slightly distally relative to Pg (0.21 mm and 0.89 mm, respectively) from T1 to T2.

The results of the correlation analyses are presented in Table V. With respect to the first hypothesis, there was a statistically significant positive correlation between B-Pg and Mn1-Pg ($r = 0.79$; $P < 0.0001$), indicating that as the mandibular incisors became posteriorly displaced during growth, the size of the chin increased. The change in position of the mandibular incisors from T1 to T2 accounts for 62% of the variance in chin development. Similarly, the change in the position of Mn6 was significantly positively correlated with the change in B-Pg ($r = 0.79$; $P < 0.0001$).

Table III. Landmarks used in the Generalized Procrustes Analysis

Point	*Landmark*
1	Condylion
2	Gonion
3	Menton
4	Pogonion
5	B-point
6	Mn1 (anterior aspect of cemento-enamel junction)
7	Mn1 (incisal tip)
8	Mn1 (posterior aspect of cemento-enamel junction)
9	Posterior edge of mandibular symphysis
10	Midpoint between landmarks 3 and 9
11	Mx1 (occlusal incisal tip)
12	Mx1 (anterior aspect of cemento-enamel junction)
13	A-point
14	Anterior nasal spine
15	Staphylion

With respect to the second hypothesis, the change in the distance from Mn1-Pg was significantly positively correlated with the change in the distance from Mx1-Pg ($r = 0.85$; $P < 0.0001$) and Mx6-Pg ($r = 0.87$; $P < 0.0001$), explaining 72% and 76% of the variance in Mn1-Pg, respectively. Similarly, the change in Mn1-Pg was significantly positively correlated with the change in A-Pg ($r = 0.76$; $P < 0.0001$), explaining 58% of the variance.

To assess whether the change in mandibular plane is a confounding factor that affects our measure of chin development, we examined the Pearson correlation (r) between mandibular plane angle (SN-MP) and chin projection (B-Pg). Developmental change in SN-MP was not correlated with developmental change in B-Pg ($r = 0.11$; $P = 0.5955$), demonstrating that mandibular rotation in the sagittal plane during development did not contribute to the change in horizontal chin projection.

A scatter plot of the principal component scores for the scaled Procrustes landmarks are found in Figure 4, A. PC1, which explains 29% of the variance in the sample, distinguishes individuals at T1 and T2. As such, this component primarily describes longitudinal changes in the sample. Individual PC scores for the first principal component between the 2 time groups were statistically significantly different (F-ratio = 32.61; $P < 0.0001$). Figure 4, B illustrates the range of shape variation along PC1. There is an increase in the prominence of the chin from T1 to T2. Moreover, there is a clear dichotomy in the growth of the upper and lower symphyseal regions of the mandible. The upper symphyseal region follows the maxilla as they migrate posteriorly from T1 to T2. In contrast, the lower border of the symphysis, along with the posterior edge of the mandibular ramus, migrates anteriorly relative to the upper symphysis and maxilla.

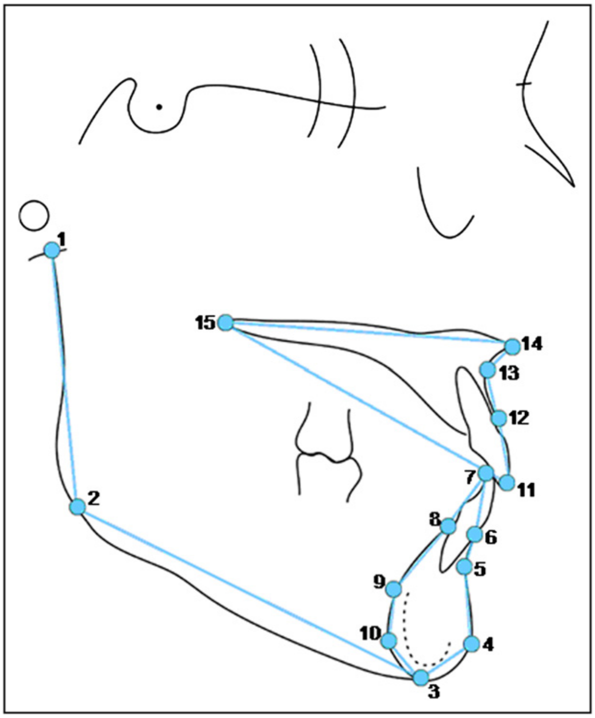

Fig 2. Coordinate landmarks shown in Table III.

DISCUSSION

The principal finding of this study is that bony chin development during adolescence occurs, in part, from differential jaw growth and compensatory dentoalveolar movements. The growth differential between the mandibular corpus and the mandibular dentition that results in projection of the chin is directly related to differential maxillary and mandibular corpus growth in the sagittal plane and is mediated by the occlusion of the teeth.

Using Pg as a stable point of reference[12-18] and measuring growth along the FH, the mandible outgrew the maxilla (at A-point) in our sample by an average of more than 4 mm from T1 to T2. This is consistent with the findings presented by You et al[20] reporting on a Class II longitudinal sample. In our sample, the posterior migration of B-point relative to Pg resulted in an increase in the horizontal chin projection, on average, of 2.34 mm. Similarly, the mandible (at Pg) outgrew the mandibular and maxillary incisors, which, along with B-point, migrated posteriorly relative to Pg during growth.

As the mandible outgrew the maxilla, in order to maintain occlusion, the maxillary teeth moved forward relative to the maxillary basal bone, and the mandibular teeth move backward relative to the mandibular basal bone. In our sample, the maxillary incisor moved back 2.76 mm at the tip relative to Pg, while A-point moved back by 4.47 mm. Thus, A-point moved back more

Table IV. Descriptive statistics for the change in variables from T1 to T2 by subtracting the measurements from the first observation (T1) from the measurements from the second observation (T2)

	Mean (mm)	*σ (mm)*	*Range (mm)*
B-Pg	2.34	1.55	7.28
A-Pg	4.47	3.58	15.96
Mn1-Pg	2.53	3.19	12.91
Mn6-Pg	0.21	3.15	12.64
Mx1-Pg	2.76	3.20	12.00
Mx6-Pg	0.89	3.46	13.60
SN-MP	−4.04*	2.68*	10.50*

*Measurement in degrees.

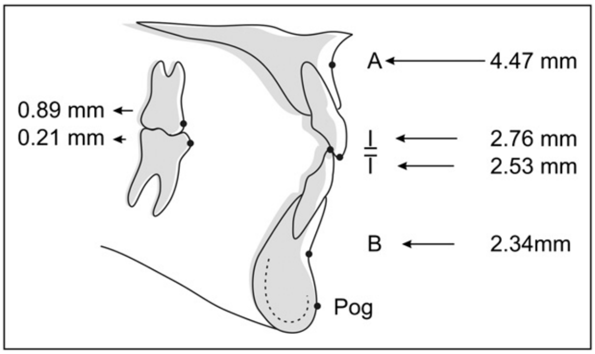

Fig 3. Mean change in A-point, B-point, maxillary incisor tip, mandibular incisor tip, maxillary first molar, and mandibular first molar relative to change in Pog T1 to T2. Dark line indicates initial time point (T1). Shading indicates final time point (T2).

than the maxillary incisor tip, so the incisor tip moved forward relative to its skeletal base. This is again consistent with the findings presented by You et al[20] for the tip of the maxillary incisor moving forward compared with A-point by 2.16 mm on average. The concordance of our data with You et al[20] suggests that dentoalveolar compensatory movements during differential jaw growth, shown to occur in untreated subjects with varying degrees of Class II malocclusion, also occur in subjects with normal occlusion. Given the variation in differential projection of the maxilla (A-point) and mandible (Pg) during growth in our sample (range = 15.96 mm shown in Table IV), and that of You et al[20] (range = 10.5 mm), the dentoalveolar compensatory mechanism appears to operate under variable jaw growth relationships.

Mandibular rotation has been shown to occur during facial growth in untreated subjects.[17,23] This type of rotation is also present in our sample (SN-MP angle, Table IV). Counterclockwise mandibular rotation during growth might alter the spatial relationship between Pg and B-point relative to the FH and influence our results. Our Pearson correlation analysis indicates that our measurement of horizontal chin projection with growth is not correlated with the mandibular plane rotation in our sample. Thus, our results are unlikely to be affected by developmental changes in mandibular plane angle.

Our first hypothesis, that the horizontal projection of the chin is a function of differential anterior growth of the lower border of the symphysis and mandibular dentition with associated alveolar bone, is largely supported by our analysis. Chin development was significantly positively correlated with the posterior migration of the mandibular incisors as predicted. Differential mandibular growth was also evident in the results of the GPA. An increase in the horizontal projection of the chin was associated with differential growth of the lower border of the symphysis (which followed the posterior border of the ramus) and the mandibular incisor and alveolar region.

The development of the chin was similarly positively correlated with the change in the position of the mandibular and maxillary molars. In contrast to the incisors, however, the molar dentition migrated only slightly distally (0.21 mm and 0.89 mm, respectively) as the size of the chin increased during growth. While this does not entirely follow from the predictions of our first hypothesis, it is likely that the lack of distal movement of the molars (especially when compared with the incisors) is affected by leeway space, which averages 1.5 mm per side for the maxillary dentition and 2.5 mm per side for the mandibular dentition.[25] As such, the molar dentition, in contrast to the anterior dentition, may not be a good proxy for the movement of the dentition, as the molars move mesially into the space created during the transition from the mixed to the permanent dentition.

Our second hypothesis, that changes in the anterior-posterior position of the mandibular dentition during growth follow concomitant changes in the maxillary dentition as a function of maxillary growth is also

Table V. Pearson correlation : *r* (lower triangle) and r^2 (upper triangle)*

	B-Pg	*A-Pg*	*Mn1-Pg*	*Mn6-Pg*	*Mx1-Pg*	*Mx6-Pg*
B-Pg	1.00	0.53	0.62	0.62	0.55	0.53
A-Pg	0.73	1.00	0.58	0.67	0.71	0.71
Mn1-Pg	0.79	0.76	1.00	0.84	0.72	0.76
Mn6-Pg	0.79	0.82	0.92	1.00	0.77	0.88
Mx1-Pg	0.74	0.84	0.85	0.88	1.00	0.71
Mx6-Pg	0.73	0.84	0.87	0.94	0.84	1.00

*All correlation coefficients are statistically significant at $P < 0.0001$.

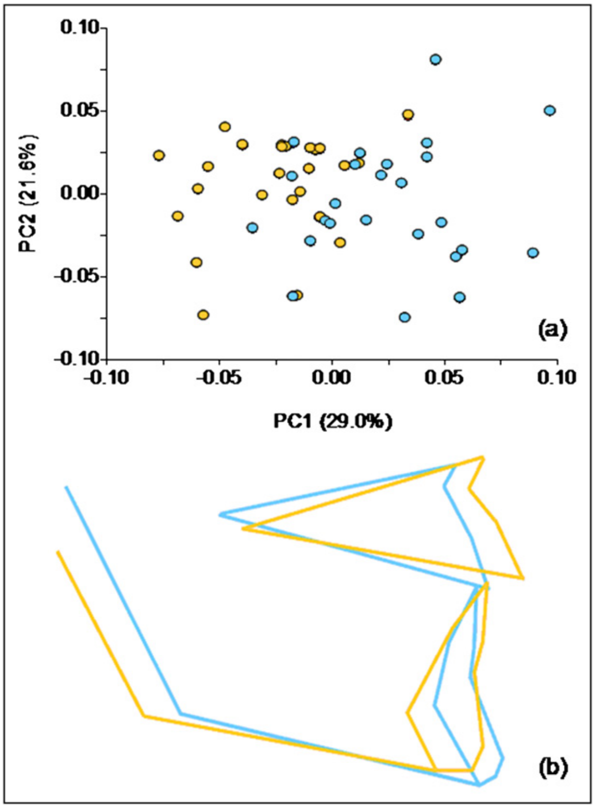

Fig 4. A, scatter plot of individual pc scores for the Procrustes scaled landmarks (orange = T1; blue = T2); **B,** shape variation along PC1 (orange = T1; blue = T2).

supported by this analysis. The posterior migration of Mn1 relative to Pg from T1 to T2 was significantly positively correlated with the posterior migration of Mx1 relative to Pg from T1 to T2. Similarly, the change in the position of Mn1 was significantly positively correlated with the relative change in the position of the maxilla. As such, the relative change in the position of Mn1 predictably followed the relative change in the maxilla and maxillary incisor. This is further supported by the results of the GPA, which indicated that the change in shape of the upper symphyseal region of the mandible was associated with a concomitant change in the maxilla.

Numerous studies have indicated that after the establishment of an occlusal relationship in the permanent dentition, the relationship is stable even in the presence of widely variable intermaxillary growth differences.[21,26-31] In our sample, occlusal relationship was maintained during growth, verified by the Class I molar occlusion observed at T1 and T2 for all our test subjects.

Numerous authors have suggested the clinical implications of occlusal interdigitation during growth. Breitner credits Kingsley as the first to suggest placement of an appliance between the teeth to unlock the occlusion ("jump the bite") in Class II patients to take advantage of forward mandibular growth.[32] In 1967, Lager[19] introduced the term "compensatory dentoalveolar development" and recommended using a bite plate in growing Class II patients to eliminate occlusal interdigitation, allowing forward movement of the mandibular dentition and improvement in the anteroposterior relationship with mandibular growth. In 1980, Solow[22] suggested that the dentoalveolar compensatory mechanism is "a system which attempts to maintain normal inter-arch relations under varying jaw relationships." In theory, after disarticulation of the occlusion, the mandibular teeth are freed to move with the mandible, allowing a differential between mandibular growth and maxillary growth (on average 4 mm in our sample) to enhance Class II correction. This freedom experienced by the mandibular dentition to move in concert with the basal mandible in the absence of occlusal interdigitation during growth has also been seen in an animal model. In a study of facial growth in *Macaca fascicularis*, disrupting the occlusion disrupts the dentoalveolar compensatory mechanism and results in more forward positioning of the mandibular dentition compared with controls.[33] Our results suggest that the dentoalveolar compensatory mechanism during growth of untreated subjects with normal occlusion is responsible for increased horizontal projection of the chin. If occlusal interdigitation and the dentoalveolar compensatory mechanism play a role in modulating the anteroposterior position of the dentition relative to basal bone during growth, apparently there are conditions of excessive mandibular growth that deny the maintenance of a stable occlusal pattern during growth. A similar analysis of untreated subjects with excessive mandibular growth may reveal differences in the temporal action of the dentoalveolar compensatory mechanism under conditions in which the rate of mandibular growth overcomes the stability of the intermaxillary occlusal relationship.

Given that the size of the chin is associated with differential growth of the upper and lower jaw, one would predict that a greater degree of facial projection is correlated with a reduction in chin development. As such, an increase in anterior growth of the mandibular and maxillary dentition would, presumably due to occlusal interdigitation, pull the mandibular dentition forward, relative to Pg, to a greater degree. This has potential implications not only for the longitudinal development of the chin in contemporary populations but also for the evolutionary development of this character as well. Mandibular symphyseal morphology in *Homo sapiens* is uniquely derived in that it is characterized by the presence of a prominent "chin,"[34,35] The development of this feature has been explained largely in terms of facial biomechanics. Our results, however, suggest that the evolutionary development of the chin may be linked to a reduction in facial projection in modern humans, specifically a reduction in forward maxillary growth relative to the mandible that may have occurred due to nonbiomechanical factors. A reduction in the size and projection of the facial skeleton has been tied to other key shape aspects of the evolution of the modern human facial skeleton.[36-38] As such, the evolutionary development of the chin may be part of a larger suite of features that are ultimately tied to the reduction in the size of the modern human facial skeleton.

CONCLUSIONS

From our analysis of the growth of a sample of untreated subjects with normal occlusion, the following conclusions are presented:

- Bony chin development during adolescence occurs, in part, from differential jaw growth and compensatory dentoalveolar movements.
- During facial growth of the mandible, the upper symphyseal region (alveolar part) is independent from the lower symphyseal region (basilar part).
- The mandibular dentition and alveolar bone are developmentally integrated with the maxilla, presumably through occlusal interdigitation.
- Occlusal interdigitation has been cited as an adaptive mechanism that allows for stable interarch dental relationships under variable jaw growth relationships, but has not, to our knowledge, been linked to the development of the chin.
- The results of this analysis have implications regarding the evolutionary development of the chin in modern humans, suggesting that the chin may be linked to an evolutionary reduction in facial projection in *Homo sapiens*.

REFERENCES

1. DuBrul E, Sicher H. The adaptive chin. Springfield: Charles C Thomas; 1954.
2. White TD. The anterior mandibular corpus of early African Hominidae: functional significance of size and shape [dissertation]. Ann Arbor: University of Michigan; 1977.
3. Daegling D. Geometry and biomechanics of hominoid mandibles [dissertation]. Stony Brook: State University of New York; 1990.
4. Daegling D. Functional morphology of the human chin. Evol Anthropol 1993;1:170-7.
5. Dobson S, Trinkaus E. Cross-sectional geometry and morphology of the mandibular symphysis in middle and late pleistocene *Homo*. J Hum Evol 2002;43:67-87.
6. Ichim I, Swain M, Kieser J. Mandibular biomechanics and development of the human chin. J Dent Res 2006;85:638-42.
7. Hrdlička A. Human dentition and teeth from the evolutionary and racial standpoint. Dom Dental J 1911:1-15.
8. Robinson L. The story of the chin. Knowledge 1913;36:410-20.
9. Waterman T. The evolution of the chin. Am Nat 1916;50:237.
10. Enlow D, Harris D. A study of the postnatal growth of the human mandible. Am J Orthod 1964;50:25-50.
11. Enlow D. A comparative study of facial growth in *Homo* and *Macaca*. Am J Phys Anthropol 1966;24:293-308.
12. Bjork A. Variations in the growth pattern of the human mandible: longitudinal radiographic study by the implant method. J Dent Res 1963;42:400-11.
13. Bjork A. Prediction of mandibular growth rotation. Am J Orthod 1969;55:585-99.
14. Kurihara S, Enlow DH, Rangel RD. Remodeling reversals in anterior parts of the human mandible and maxilla. Angle Orthod 1989;50:98-106.
15. Baumrind S, Ben-Bassat Y, Korn E, Bravo L, Curry S. Mandibular remodeling measured on cephalograms: 2. A comparison of information from implant and anatomic best-fit superimpositions. Am J Orthod Dentofacial Orthop 1992;102:227-38.
16. Buschang P, Gandini L. Mandibular skeletal growth and modeling between 10 and 15 years of age. Eur J Orthod 2002;24:69-79.
17. Gu Y, McNamara A Jr. Mandibular growth changes and cervical vertebral maturation. Angle Orthod 2007;77:947-53.
18. Chen SYY, Lestrel PE, Kerr WJS, McColl JH. Describing shape changes in the human mandible using elliptical Fourier functions. Eur J Orthod 2000;22:205-16.
19. Lager H. The individual growth pattern and stage of maturation as a basis for treatment of distal occlusion with overjet. Trans Eur Orthod 1967;135-45.
20. You Z, Fishman L, Rosenblum R, Subtelny J. Dentoalveolar changes related to mandibular forward growth in untreated class II persons. Am J Orthod Dentofacial Orthop 2001;120:598-607.
21. Harris EF, Behrents RG. The intrinsic stability of class I molar relationship: a longitudinal study of untreated cases. Am J Orthod Dentofacial Orthop 1988;94:63-7.
22. Solow B. The dentoalveolar compensatory mechanism: background and clinical implications. Br J Orthod 1980;7:145-61.
23. Riolo ML, Moyers RE, McNamara JA, Hunter WS. An atlas of craniofacial growth: cephalometric standards from the University

School Growth Study. Ann Arbor: Center for Human Growth and Development, University of Michigan; 1974.

24. Rohlf FJ. 1990. Rotational fit (Procrustes) methods. In: Rohlf FJ, Bookstein FL, editors. Proceedings of the Michigan Morphometrics Workshop. Ann Arbor: University of Michigan Museum of Zoology;1990. p. 227–36.
25. Proffit W. Contemporary Orthodontics. 3rd ed. Mosby; 2000.
26. Subtelny JD. "To treat or not to treat". Int Dent J 1973;23: 292-303.
27. Carter NE. Dentofacial changes in untreated class II division 1 subjects. Br J Orthod 1987;14:225-35.
28. Bishara SE, Jacobsen JR, Vorhies B, Bayati P. Changes in dentofacial structures in untreated class II division 1 and normal subjects: a longitudinal study. Angle Orthod 1999;67:55-66.
29. Fröhlich FJ. A longitudinal study of untreated class II type malocclusions. Trans Eur Orthod Soc 1963;37:137-59.
30. Feldmann I, Lundström F, Peck S. Occlusal changes from adolescence to adulthood in untreated patients with class II division 1 deepbite malocclusion. Angle Orthod 1999;69:33-8.
31. Arya B, Savara B, Thomas D. Prediction of first molar occlusion. Am J Orthod 1973;63:610-21.
32. Breitner C. Bone changes from experimental orthodontic treatment. Am J Orthod Oral Surg 1940;26:521-47.
33. Ostyn J, Maltha J, van der Linden F. The role of interdigitation in sagittal growth of the maxillomandibular complex in Macaca fascicularis. Am J Orthod Dentofacial Orthop 1996; 109:71-8.
34. Lieberman DE. 1995. Testing hypotheses about recent human evolution from skulls: integrating morphology, function, development, and phylogeny. Curr Anthropol 36:159–97.
35. Lieberman DE, McBratney BM, Krovitz G. 2002. The evolution and development of cranial form in Homo sapiens. Proc Nat Acad Sci 99:1134–9.
36. Franciscus RG, Holton NE, Nieves MA, et al. Experimental facial growth alteration in *Sus scrofa* and its implications for the evolution of modern human craniofacial anatomy. Am J Phys Anthropol 2008;135:98.
37. Holton NE, Franciscus RG. The paradox of a wide nasal aperture in cold-adapted Neanderthals: a causal assessment. J Hum Evol 2008;55:942-51.
38. Maddux SD, Franciscus RG. Allometric scaling of infraorbital surface topography in Homo. J Hum Evol 2009;56:161-174.