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Geometric morphometric analysis of growth patterns among facial types

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Abstract

Introduction: Extreme patterns of vertical facial divergence are of great importance to clinicians because of their association with dental malocclusion and functional problems of the orofacial complex. Understanding the growth patterns associated with vertical facial divergence is critical for clinicians to provide optimal treatment. This study evaluates and compares growth patterns from childhood to adulthood among 3 classifications of vertical facial divergence using longitudinal, lateral cephalograms from the Craniofacial Growth Consortium Study.

Methods: Participants (183 females, 188 males) were classified into 1 of 3 facial types on the basis of their adult mandibular plane angle (MPA): hyperdivergent (MPA >39°; n = 40), normodivergent (28° ≤ MPA ≤ 39°; n = 216), and hypodivergent (MPA <28°; n = 115). Each

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individual had 5 cephalograms between ages 6 and 20 years. A set of 36 cephalometric landmarks were digitized on each cephalogram. Landmark configurations were superimposed to align 5 homologous landmarks of the anterior cranial base and scaled to unit centroid size. Growth trajectories were calculated using multivariate regression for each facial type and sex combination.

Results: Divergent growth trajectories were identified among facial types, finding more similarities in normodivergent and hypodivergent growth patterns than either share with the hyperdivergent group. Through the use of geometric morphometric methods, new patterns of facial growth related to vertical facial divergence were identified. Hyperdivergent growth exhibits a downward rotation of the maxillomandibular complex relative to the anterior cranial base, in addition to the increased relative growth of the lower anterior face. Conversely, normodivergent and hypodivergent groups exhibit stable positioning of the maxilla relative to the anterior cranial base, with the forward rotation of the mandible. Furthermore, the hyperdivergent maxilla and mandible become relatively shorter and posteriorly positioned with age compared with the other groups.

Conclusions: This study demonstrates how hyperdivergent growth, particularly restricted growth and positioning of the maxilla, results in a higher potential risk for Class II malocclusion. Future work will investigate growth patterns within each classification of facial divergence.

Classifications of facial and dental morphology are frequently used in orthodontic practice for diagnosis, treatment planning, and prognosis. Schudy[1] first characterized the interaction of vertical and anteroposterior growth in the face as patterns of facial divergence (ie, hyperdivergent, normodivergent, and hypodivergent), and since then, additional terminology has been used to describe similar morphologic patterns. The hyperdivergent skeletal pattern has been referred to as an open bite[2–4] or long face syndrome,[5–7] and the hypodivergent pattern as a deep bite[2–4] or short face syndrome.[6,8] Although Schudy's[1] classification system was based on the mandibular plane angle (MPA), other measurements have been used to classify patterns of vertical facial divergence, including the anterior to posterior facial height ratio,[6] the lower anterior to total anterior facial height ratio,[2–4] and the angle between mandibular and Frankfort horizontal planes.[6]

The clinical significance of these classifications relates to their associations with dental malocclusion and other functional or esthetic issues. The hyperdivergent facial type is commonly associated with an anterior open bite referring to a lack of vertical overlap in maxillary and mandibular incisors.[9] Furthermore, skeletal hyperdivergence is related to reduced masticatory performance[10–13] and airway constriction.[14] The hypodivergent facial type has been linked to a deep or excessive vertical overbite of the maxillary and mandibular incisors, which can interfere with lateral and anterior mandibular movements and temporomandibular joint dysfunction.[15,16]

Understanding differences in morphology and growth associated with vertical facial divergence patterns is critical for providing appropriate treatment and prognoses for participants. Morphologic differences among skeletal facial types are apparent around 5 or 6 years of age.[6,17–20] Most studies agree that facial type differences are predominantly found in the lower face and mandible, but the specific measurements that differ among facial types vary by study.[6,17–19,21,22]

Previous cephalometric analyses of linear distance and angular measurements describing childhood and/or adolescent growth patterns across facial types have also found contrasting results. For example, Bishara and Jakobsen[6] note parallel incremental growth curves for many craniofacial measurements from 5 to 25 years of age, indicating measurement differences among facial types were already present at 5 years of age, with similar subsequent growth patterns. Conversely, Karlsen[17,18] reported differences in growth up to 12 years of age among facial types, whereas Nanda[2] found variation in the adolescent growth spurt among facial types leading to increased measurement differences during adolescence. These disagreements likely result from the use of different study samples, classification methods, or the age at classification, requiring further work to harmonize previous studies.

In this analysis, we use geometric morphometric methods (GMM), a multivariate, landmark-based approach to evaluate differences in craniofacial morphology and growth patterns among 3 skeletal facial types. The GMM approach allows for the evaluation of coordinated patterns of vertical and anteroposterior growth in craniofacial structures by preserving the geometric or spatial relationships of landmarks throughout the analysis, which traditional linear cephalometrics are poorly equipped to quantify. We used the strengths of this approach to clarify inconsistencies among previous studies of craniofacial growth patterns of hyperdivergent, normodivergent, and hypodivergent participants. The goals of this study are to (1) describe and compare growth trajectories for hyperdivergent, normodivergent, and hypodivergent facial types and (2) determine shape differences among facial types at different ages.

MATERIAL AND METHODS

The Craniofacial Growth Consortium Study houses longitudinal, lateral cephalograms from 6 historical growth studies in the United States, which sampled populations of primarily European ancestry from 1930-1982.[19,20,23] A total of 1855 cephalograms from 371 participants (183 females, 188 males) in the Craniofacial Growth Consortium Study were included in this analysis. Each individual had 1 cephalogram taken within each of the following age categories: 6-8, 9-11, 12-14, 15-17, and 18-20 years, for a total of 5 cephalograms per participant. If a participant had more than 1 cephalogram per age category, the cephalogram taken closest to the median age for that category was selected.

The age range of 6-20 years, and associated age categories, were chosen to maximize the available sample, which includes the primary period for clinical treatment related to facial growth. Some previous studies have considered the importance of postadolescent changes in facial dimensions,[24–31] although the amount and clinical significance of this growth have been debated.[24,25,28] The greatest magnitude of postadolescent growth is often observed in anterior facial height but rarely exceeds 1 mm over 10 years, a suggested threshold for clinical significance.[25]

Facial type classification was based on adult morphology for all participants using their cephalograms in the 18-20 year age interval; these classifications were applied to juvenile cephalograms from the same participants. MPA, the angle between sella-nasion and gonion-menton, was calculated and used for facial type classification: hypodivergent (MPA <28°), normodivergent (28° ≤ MPA ≤ 39°), and hyperdivergent (MPA >39°) (Table I). A set of 36 cephalometric landmarks (Table II; Fig 1) was collected on each cephalogram, with no missing data, to quantify the morphology of the craniofacial skeleton and anterior dentition. This study was approved by the University of Missouri Institutional Review Board.

For each sex, a modified generalized Procrustes analysis was used to align landmark configurations by removing variation in location, rotation, and scale so that only differences in shape remained.[32,33] Each landmark configuration was superimposed to align 5 homologous landmarks of the anterior cranial base but scaled to the unit centroid size of the entire landmark configuration (see Table II; Fig 1). The resulting aligned landmark coordinates were used as shape variables in subsequent analyses.

To model growth trajectories, multivariate regressions of the shape variables on age[34,35] were performed for each adult facial type, separately by sex. In this context, we specifically refer to growth trajectories as changes in landmark configurations (ie, shape change) with age. For each of the 6 facial type and sex combinations, 4 different models were fit (linear to fourth-order polynomial). Leave-one-out cross-validation and mean squared error values were used to select the best fit models. Predicted shapes were calculated for the 6 selected models at 1-year age intervals, from 6-20 years, to represent annual mean shape estimates for each trajectory. Pairwise permutation tests, described by Mitteroecker et al,[34] were used to test identical trajectories among the 3 facial types using the residual sum of squares as a test statistic with 10,000 iterations.

Facial type growth trajectories were compared, by sex, using a principal component analysis of age-shape space, which is a principal component analysis of the matrix of predicted shape coordinates with an additional column for age (cf, Mitteroecker et al[36]). Growth patterns for each facial type were visualized using wireframe plots to compare the shape change within each trajectory at ages 6, 10, 14, and 18 years.[37] Comparisons were also made between the hyperdivergent and hypodivergent landmark configurations at these ages to visualize morphologic differences between the most extreme facial types.

Three angular measurements, SNA (sella-nasion-point A), SNB (sella-nasion-point B), and ANB (point A-nasion-point B), were calculated for each cephalogram to demonstrate the change in anteroposterior (A-P) maxillomandibular relationships with age, across facial types. Although relative maxillomandibular relationships are visualized using GMM, the SNA, SNB, and ANB angles are provided for comparison as clinically important cephalometric measurements for identifying interactions with anteroposterior relationships (ie, Class I, II, and III). One-way analysis of variance with post-hoc Tukey’s Honest Significant Difference test was used to test significant differences in each angle among facial types by sex and age group. All analyses were performed in R using the Morpho,[38] geomorph,[39] and stats packages.[40]

RESULTS

For each of the 6 facial type and sex combinations, quadratic models were selected for multivariate regressions of shape variables on age (Table III). In females and males, the first principal component axis of age-shape space describes variation in age and patterns of age-correlated shape. When plotted against age, the second principal component axis distinguishes hyperdivergent and hypodivergent trajectories, with the normodivergent trajectory between them (Fig 2). The differences in growth trajectories represent unique patterns of average craniofacial growth for each facial type. In females, the 3 trajectories become increasingly parallel at older ages, whereas, in males, the hyperdivergent and hypodivergent trajectories continue to diverge from the normodivergent trajectory. Raw data for each individual are projected onto the age-shape axes to visualize the individual variation within each facial type (Fig 2). Individual trajectories overlap among facial types, but permutation tests indicate significantly different trajectories for each facial type ($P \leq 0.0003$ for all comparisons) (Table IV).

Growth patterns within each facial type trajectory are presented in Figure 3 by visualizing predicted landmark configurations at ages 6, 10, 14, and 18 years by sex. In both females and males, the hyperdivergent type exhibits slight anteriorly downward rotation of the maxilla from ages 6 to 10 years, with little rotation occurring after age 10 years. The maxilla also becomes relatively shorter with age, and the subnasal region (ANS-point A-prosthion) becomes increasingly concave. At each subsequent age, the mandibular ramus becomes more vertically oriented, resulting in a more anterior position of the condyle and coronoid process with corresponding backward rotation of the corpus. The backward rotation of the corpus also coincides with a relatively taller mandibular symphysis.

Slight downward rotation of the anterior maxilla from ages 6 to 10 years is also present in the normodivergent and hypodivergent types. Similar to growth in the hyperdivergent type, the normodivergent type exhibits a more vertical orientation of the mandibular ramus but with no corresponding backward rotation of the corpus. As the normodivergent corpus becomes relatively longer with age, the mandibular symphysis projects more anteriorly with no change in relative height. The hypodivergent growth pattern does not depict as much change in the orientation of the ramus, but the corpus rotates forward with a greater projection of the chin. In both normodivergent and hypodivergent trajectories, the antegonial notch flattens from ages 6 to 18 years.

In males, growth patterns within each facial type are very similar to those in females, but the magnitude of shape change and degree of rotation is greater (Fig 3). In females, there is less change in facial shape between ages 14 and 18 years, whereas there is still considerable shape change between ages 14 and 18 years in males, likely an indication of an earlier cessation of growth in females compared with males.

Comparisons of hypodivergent and hyperdivergent face shapes at different ages (Fig 4) show that distinct morphologies are present at 6 years of age and persist to 18 years of age in both sexes. At each age interval, the hyperdivergent face differs from the hypodivergent face by a larger gonial angle with a more distinct antegonial notch, smaller posterior facial height, shorter length of the posterior cranial base, a narrower mandibular ramus, anterior (or forward) rotation of the ramus, backward rotation of the mandibular corpus, downward rotation of the anterior maxilla, greater subnasal height, and greater upper and lower anterior dentoalveolar heights (Fig 4). The more vertical orientation of the mandibular ramus in the hyperdivergent face results in a higher positioned condyle and coronoid process. The lengths of the maxilla and mandible are relatively shorter and posteriorly positioned in the hyperdivergent face compared with the hypodivergent face. Furthermore, the hyperdivergent maxillary and mandibular incisors exhibit reduced overlap compared with hypodivergent maxillary and mandibular incisors.

The smaller SNA and SNB angles in the hyperdivergent type demonstrate the retrognathic positioning of both the maxilla and mandible compared with other facial types (Fig 5; Table V). SNA and SNB angles increase with age to a lesser degree in the hyperdivergent group than the hypodivergent and normodivergent groups. Furthermore, the hyperdivergent ANB angle is, on average, larger compared with other facial types indicating a more retrognathic mandible relative to the maxilla, but this difference is statistically significant at all ages only in females.

DISCUSSION

In this study, we used GMM to evaluate and compare growth trajectories among different clinical classifications of vertical facial divergence. The strength of GMM is the preservation of geometric relationships and the orientation of structures as configurations of landmarks allowing for the evaluation of coordinated patterns of vertical and anteroposterior growth in the craniofacial complex. This landmark-based approach is novel to studies of craniofacial growth related to clinical classifications of facial morphology as previous work has focused on modeling the growth of linear distance measurements or isolated interlandmark angles of the face. In contrast, GMM uses information about the spatial relationships among all of the landmarks simultaneously.

Growth models based on distance measurements are very useful for evaluating the timing and changes in growth velocity among individual measurements; however, traditional linear cephalometries are poorly equipped to quantify the spatial relationships among variables or measurements. For example, it is possible for landmark positions or orientations to change from one configuration to another even if the linear distance itself does not change. In this situation, shape change would be very difficult to detect by studying linear measurements and would require a complicated simultaneous interpretation of multiple such measurements; GMM is designed to overcome this challenge.

This study builds on previous analyses of growth related to vertical facial classifications by identifying nuanced differences in the growth and orientation of facial components among vertical skeletal facial types. The identification here of novel correlative anatomic change provides a better understanding of structural relationships that can ultimately lead to improved growth modification strategies. Differences in results among previous studies have often been attributed to variation among sample populations and classification procedures. Some studies have included only participants with the most extreme hyperdivergent and hypodivergent conditions[2,6] or have restricted the sample to only those with Class I malocclusion.[6] In this study, we included all participants within the classification ranges to fully represent the variation within each facial type. Furthermore, we include all participants with Class I, II, and III malocclusions to examine the full range of vertical and anteroposterior relationships across facial types. We also determined facial type classifications using cephalograms in the oldest age group (18-20 years). This approach allows for maximum morphologic distinction among facial types and assessment of how the adult facial morphology was achieved during growth and development. Other studies have classified participants during the adolescent growth spurt,[2,4,17,18,41] or during childhood.[6]

This analysis indicates that some differences in average morphology among the 3 facial types are established by 6 years of age, as previously noted.[6,19] Nevertheless, here we show that each type follows a unique average growth trajectory until adulthood, indicating different adolescent growth patterns,[2,4,17,41] with hypodivergent and normodivergent growth patterns more similar to each other than either is to the hyperdivergent growth pattern (Fig 2). These findings suggest the need for a nuanced interpretation of growth when attempting to estimate future face shape that accounts not only for early established differences in morphology but also the distinct growth trajectories among facial types that will further contribute to differences in face shape at later ages.

The differences in growth trajectories among facial types also vary by sex. Male trajectories continue to diverge through 20 years of age, whereas the female trajectories become nearly parallel by age 18 years (Fig 2). The near-parallel trend in females compared with males is likely the result of the earlier cessation of adolescent craniofacial growth in females than males, with minor changes in later facial shape from postadolescent growth.[42] The diverging male growth trajectories reflect the continued differential growth of craniofacial structures and would be expected to approach a near-parallel configuration, similar to females, during postadolescent growth.

The results of this study suggest that morphologic differences between hyperdivergent and hypodivergent types result from coordinated changes in the orientation of the maxilla and mandible relative to the anterior cranial base, in conjunction with differences in anterior facial growth. In comparison with the average hypodivergent configurations, the hyperdivergent mandible and maxilla are rotated downward and backward, relative to the anterior cranial base, resulting in superior and anterior positioning of the mandibular condyle, downward rotation of the palatal plane anteriorly, and backward rotation of the mandibular corpus (Fig 4). The degree of rotation is greatest in the corpus. Backward rotation of the mandibular corpus in the hyperdivergent configuration also corresponds with an increase in relative lower anterior facial height, in contrast to the forward mandibular rotation and reduction in relative lower anterior facial height exhibited in hypodivergent growth. Differences in both posterior and anterior facial heights among facial types, manifest in part by coordinated maxillomandibular orientation, are supported by previous work.[17,22] Our results contrast with Nanda[2] and others[4,41,43] who have argued that these morphologic differences are associated primarily with differential growth in the vertical anterior dimensions of the face with little difference in posterior facial height among classifications.

When facial type was determined using the ratio of lower anterior facial height to total anterior facial height, rather than MPA, Enoki et al[43] found that participants with smaller lower anterior facial heights (ANS-Me) have palatal planes that are rotated downward compared with participants with greater lower anterior facial height. Despite the noted difference in the angle from the mandibular plane to the palatal plane, Enoki et al[43] found there was no difference in MPA by facial type. This contrasts with the findings of the current study that identify downward palatal plane rotation in the hyperdivergent face with a corresponding increase in lower anterior facial height. These contrasting results may stem from the use of different classification systems; the MPA in the current study and the ratio of lower anterior facial height to total anterior facial height by Enoki et al.[43]

As demonstrated by both the geometric and traditional morphometric analyses in this study (Figs 3 and 5), the hyperdivergent maxilla and mandible are relatively shorter and posteriorly positioned than the hypodivergent facial type, with this difference becoming more pronounced with age. In the hyperdivergent face, the relative anterior positioning of the mandible does not change substantially, but the maxilla becomes relatively shorter with age. Conversely, the hypodivergent face exhibits an increase in relative mandibular length with age, but relative maxillary length remains unchanged. These results are contrary to those found by Bishara and Jakobsen[6] and Opdebeeck et al,[8] who identified no difference in mandibular or maxillary length among facial types. Our results are supported by the A-P relationships of the maxilla and mandible found by Joseph et al[14] using SNA and SNB angles, and Opdebeeck et al[8] also find a more retrusive position of the maxilla in the hyperdivergent group.

The observations reported in this study have clinical implications for understanding how and when features associated with vertical facial divergence arise. The identification of morphologic features indicative of facial divergence at younger ages can help improve the capacity of clinicians to diagnose and treat participants. Gonial angle and dentoalveolar height are mandibular features previously identified as good predictors of adult facial type at young ages.[19] In this study, these features, in addition to the depth of the antegonial notch and height of the subnasal maxillary region as described above, were also found to distinguish hyperdivergent and hypodivergent facial patterns at 6 years of age.

Furthermore, patterns of facial divergence are often associated with different types of malocclusion. This analysis demonstrates how the A-P relationships of the maxilla and mandible change with age across facial types. In the normodivergent and hypodivergent types, forward rotation and elongation of the mandible, while maintaining proportional growth of the maxilla, effectively reduces the ANB angle over time. However, the A-P positioning of the mandible relative to the maxilla in the hyperdivergent face does not change substantially, with slightly greater anterior growth of the mandible than the maxilla. This suggests a greater propensity for maintaining a higher ANB angle and Class II malocclusion in the hyperdivergent group.

CONCLUSIONS

In this study, we find distinct patterns of craniofacial growth among the 3 classifications of vertical facial morphology (hyperdivergent, normodivergent, and hypodivergent). Patterns of growth are more similar among normodivergent and hypodivergent groups, with the magnitude of change being greater in the latter. Key morphologic differences among facial types were already present by age 6 years and intensified through adolescence. Much of the variation is concentrated in the shape and growth of the mandible, but differences were also present in the orientation and relative A-P dimension of the maxilla, indicating different patterns of coordinated maxillary and mandibular growth. Specifically, these results demonstrate that the downward and backward rotation of both the maxilla and mandible in conjunction with restricted relative maxillary growth in the hyperdivergent face may lead to increased risk for Class II malocclusions. Further analysis is needed to identify under what conditions vertical hyperdivergence may result in satisfactory or deficient A-P growth. This study will serve as a foundation for future work evaluating growth patterns within facial types and in conjunction with other vertical and A-P malocclusions.

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REFERENCES

1. Schudy F. Vertical growth versus anteroposterior growth as related to function and treatment. Angle Orthod1964;34:75–93.
2. Nanda SK. Patterns of vertical growth in the face. Am J Orthod Dentofacial Orthop1988;93:103–16. [PubMed: 3422525]
3. Nanda SK. Growth patterns in subjects with long and short faces. Am J Orthod Dentofacial Orthop1990;98:247–58. [PubMed: 2403077]
4. Moon SC, Kim HK, Kwon TK, Han SH, An CH, Park YS. Patterns of vertical facial growth in Korean adolescents analyzed with mixed-effects regression analysis. Am J Orthod Dentofacial Orthop2013;143:810–8. [PubMed: 23726331]
5. Schendel SA, Eisenfeld J, Bell WH, Epker BN, Mishelevich DJ. The long face syndrome: vertical maxillary excess. Am J Orthod1976;70:398–408. [PubMed: 1067758]
6. Bishara SE, Jakobsen JR. Longitudinal changes in three normal facial types. Am J Orthod1985;88:466–502. [PubMed: 3878083]
7. Björk A, Skieller V. Contrasting mandibular growth and facial development in long face syndrome, juvenile rheumatoid polyarthritis, and mandibulofacial dysostosis. J Craniofac Genet Dev Biol Suppl1985;1:127–38. [PubMed: 3877091]
8. Opdebeeck H, Bell WH. The short face syndrome. Am J Orthod1978;73:499–511. [PubMed: 277066]
9. Proffit W, Fields H Jr, Sarver D. Contemporary Orthodontics. 5th ed.St Louis: Mosby; 2012.
10. Proffit WR, Fields HW, Nixon WL. Occlusal forces in normal- and long-face adults. J Dent Res1983;62:566–70. [PubMed: 6573373]
11. Proffit WR, Fields HW. Occlusal forces in normal- and long-face children. J Dent Res1983;62:571–4. [PubMed: 6573374]
12. Ingervall B, Minder C. Correlation between maximum bite force and facial morphology in children. Angle Orthod1997;67:415–22: discussion 423-4. [PubMed: 9428959]

13. Cha BK, Kim CH, Baek SH. Skeletal sagittal and vertical facial types and electromyographic activity of the masticatory muscle. Angle Orthod2007;77:463–70. [PubMed: 17465654]

14. Joseph AA, Elbaum J, Cisneros GJ, Eisig SB. A cephalometric comparative study of the soft tissue airway dimensions in persons with hyperdivergent and normodivergent facial patterns. J Oral Maxillofac Surg1998;56:135–9: discussion 139-40. [PubMed: 9461134]

15. Riolo ML, Brandt D, TenHave TR. Associations between occlusal characteristics and signs and symptoms of TMJ dysfunction in children and young adults. Am J Orthod Dentofacial Orthop1987;92:467–77. [PubMed: 3500634]

16. Bergersen EO. A longitudinal study of anterior vertical overbite from eight to twenty years of age. Angle Orthod1988;58:237–56. [PubMed: 3189955]

17. Karlsen AT. Craniofacial growth differences between low and high MP-SN angle males: a longitudinal study. Angle Orthod1995;65:341–50. [PubMed: 8526293]

18. Karlsen AT. Association between facial height development and mandibular growth rotation in low and high MP-SN angle faces: a longitudinal study. Angle Orthod1997;67:103–10. [PubMed: 9107374]

19. Oh H, Knigge R, Hardin A, Sherwood R, Duren D, Valiathan M, et al.Predicting adult facial type from mandibular landmark data at young ages. Orthod Craniofac Res2019;22(Suppl 1):154–62. [PubMed: 31074133]

20. Hardin AM, Valiathan M, Oh H, Knigge RP, McNulty KP, Leary EV, et al.Clinical implications of age-related change of the mandibular plane angle. Orthod Craniofac Res2020;23:50–8. [PubMed: 31465622]

21. Bishara SE, Augspurger EF. The role of mandibular plane inclination in orthodontic diagnosis. Angle Orthod1975;45:273–81. [PubMed: 1059340]

22. Björk A, Skieller V. Normal and abnormal growth of the mandible. A synthesis of longitudinal cephalometric implant studies over a period of 25 years. Eur J Orthod1983;5:1–46. [PubMed: 6572593]

23. Sherwood RJ, Oh HS, Valiathan M, et al.Bayesian approach to longitudinal craniofacial growth: the craniofacial growth consortium study. Anat Rec2021;304:991–1019.

24. Bishara SE, Treder JE, Jakobsen JR. Facial and dental changes in adulthood. Am J Orthod Dentofacial Orthop1994;106:175–86. [PubMed: 8059754]

25. Bondevik OGrowth changes in the cranial base and the face: a longitudinal cephalometric study of linear and angular changes in adult Norwegians. Eur J Orthod1995;17:525–32. [PubMed: 8682170]

26. Forsberg CM. Facial morphology and ageing: a longitudinal cephalometric investigation of young adults. Eur J Orthod1979;1:15–23. [PubMed: 296926]

27. Forsberg CM, Eliasson S, Westergren H. Face height and tooth eruption in adults–a 20-year follow-up investigation. Eur J Orthod1991;13:249–54. [PubMed: 1915613]

28. Fudalej P, Kokich VG, Leroux B. Determining the cessation of vertical growth of the craniofacial structures to facilitate placement of single-tooth implants. Am J Orthod Dentofacial Orthop2007;131(4 Suppl):S59–67. [PubMed: 17448387]

29. Thilander B, Persson M, Adolfsson U. Roentgen-cephalometric standards for a Swedish population. A longitudinal study between the ages of 5 and 31 years. Eur J Orthod2005;27:370–89. [PubMed: 16043474]

30. Behrents RG. Growth in the Aging Craniofacial Skeleton. Ann Arbor: University of Michigan; 1985.

31. Tallgren AThe effect of denture wearing on facial morphology. A 7-year longitudinal study. Acta Odontol Scand1967;25:563–92. [PubMed: 5247241]

32. Gower JC. Generalized Procrustes analysis. Psychometrika1975; 40:33–51.

33. Rohlf FJ, Slice D. Extensions of the Procrustes method for the optimal superimposition of landmarks. Syst Zool1990;39:40.

34. Mitteroecker P, Gunz P, Bookstein FL. Heterochrony and geometric morphometrics: a comparison of cranial growth in *Pan paniscus* versus *Pan troglodytes*. Evol Dev2005;7:244–58. [PubMed: 15876197]

35. Bulygina E, Mitteroecker P, Aiello L. Ontogeny of facial dimorphism and patterns of individual development within one human population. Am J Phys Anthropol2006;131:432–43. [PubMed: 16596605]
36. Mitteroecker P, Gunz P, Bernhard M, Schaefer K, Bookstein FL. Comparison of cranial ontogenetic trajectories among great apes and humans. J Hum Evol2004;46:679–97. [PubMed: 15183670]
37. Bookstein FL. Morphometric Tools for Landmark Data: Geometry and Biology. Cambridge: Cambridge University Press; 1991.
38. Schlager S. Morpho and Rvcg - shape analysis in R. In: Zheng G, Li S, Szekely G, editors. Statistical Shape and Deformation Analysis. Cambridge: Academic Press; 2017. p. 217–56.
39. Adams D, Collyer M, Kaliontzopoulou A, Baken E. Geomorph: geometric morphometric analyses of 2D/3D landmark data. Available at: https://cran.r-project.org/package=geomorph.Accessed June 11, 2021.
40. R Core Team. R: a language and environment for statistical computing. Available at: https://www.R-project.org/.Accessed June 11, 2021.
41. Han SH, Park YS. Growth patterns and overbite depth indicators of long and short faces in Korean adolescents: revisited through mixed-effects analysis. Orthod Craniofac Res2019;22:38–45. [PubMed: 30450776]
42. Nahhas RW, Valiathan M, Sherwood RJ. Variation in timing, duration, intensity, and direction of adolescent growth in the mandible, maxilla, and cranial base: the Fels longitudinal study. Anat Rec (Hoboken)2014;297:1195–207. [PubMed: 24737730]
43. Enoki C, Telles Cde S, Matsumoto MAN.Dental-skeletal dimensions in growing individuals with variations in the lower facial height. Braz Dent J2004;15:68–74. [PubMed: 15322649]

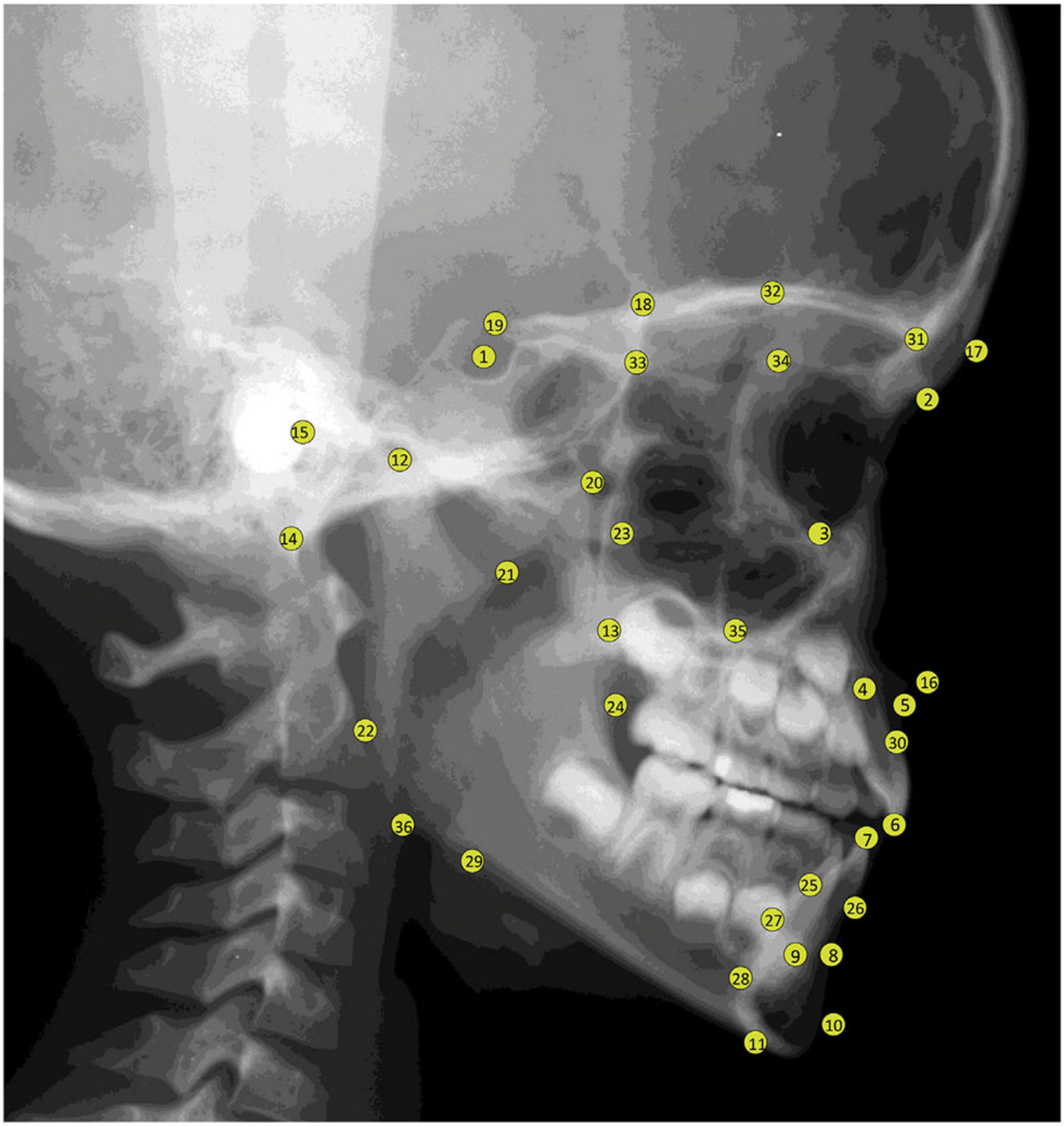

Fig 1.
Depiction of cephalometric landmarks used in this study. Landmark numbers correspond to descriptions in Table II. Landmarks 18, 19, 32, 33, and 34 represent homologous points of the anterior cranial base used in superimposition.

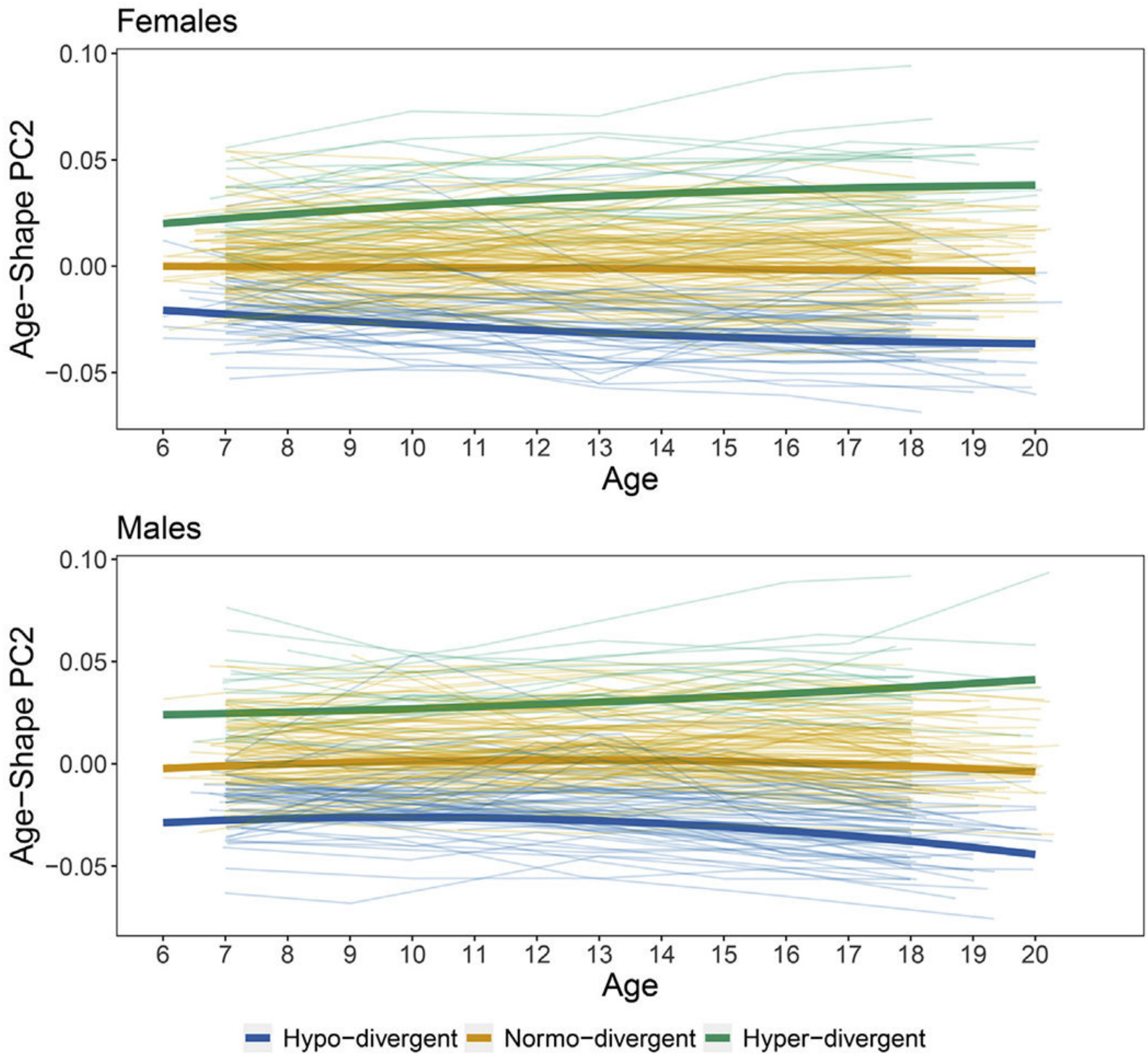

Fig 2.

A plot of second principal component (PC2) of age-shape space against chronological age for females (*top*) and males (*bottom*). Each line represents a growth trajectory (ie, shape change of a landmark configuration) with age. The thick lines represent the average trajectories for each facial type, with thin lines representing participants (*blue*, hypodivergent; *yellow*, normodivergent; and *green*, hyperdivergent).

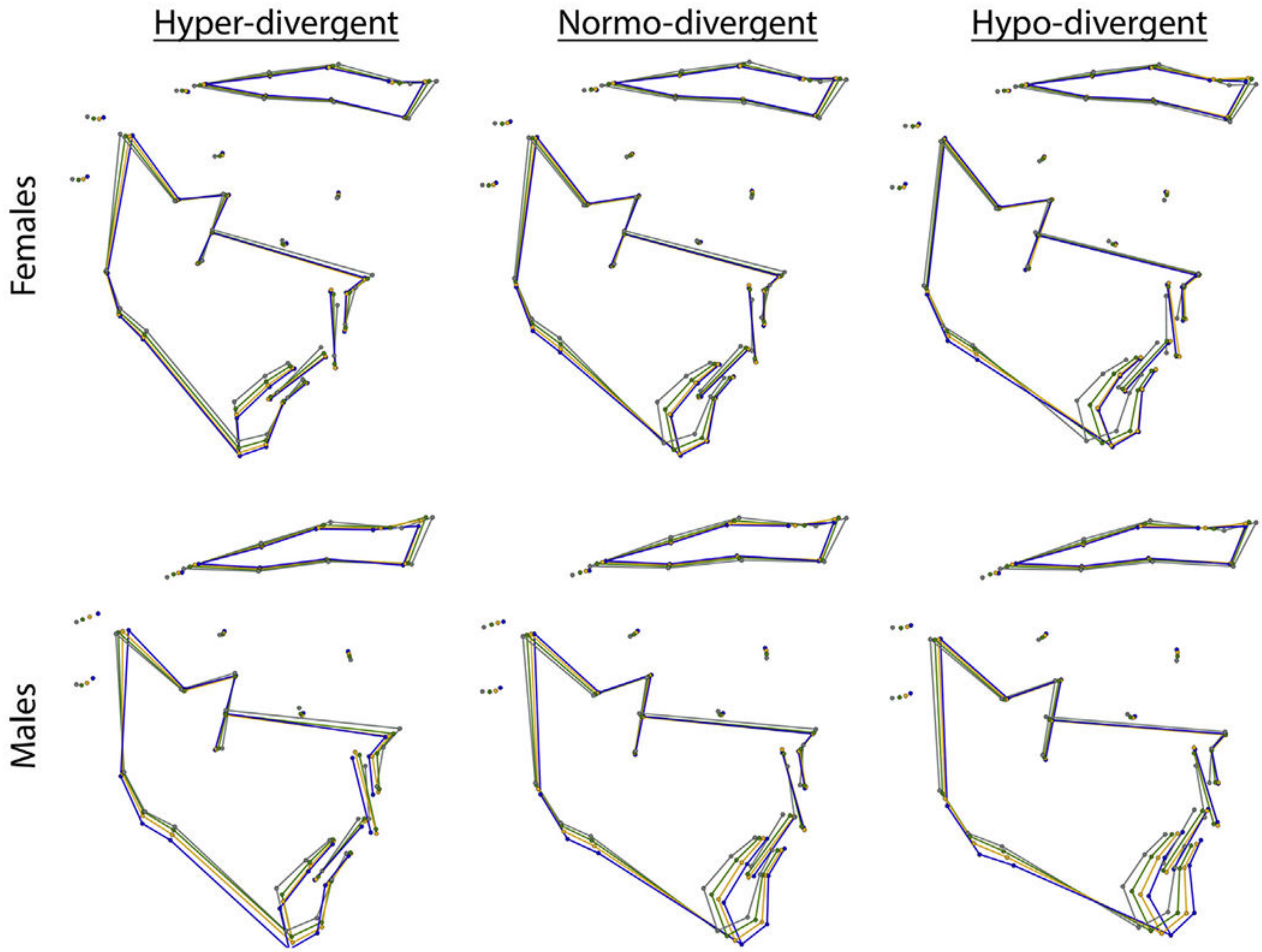

Fig 3.

Visualization of the shape change along each facial type and sex growth trajectory shown in Figure 2 as represented by landmark configurations estimated at ages 6 (*gray*), 10 (*green*), 14 (*yellow*), and 18 (*blue*) years.

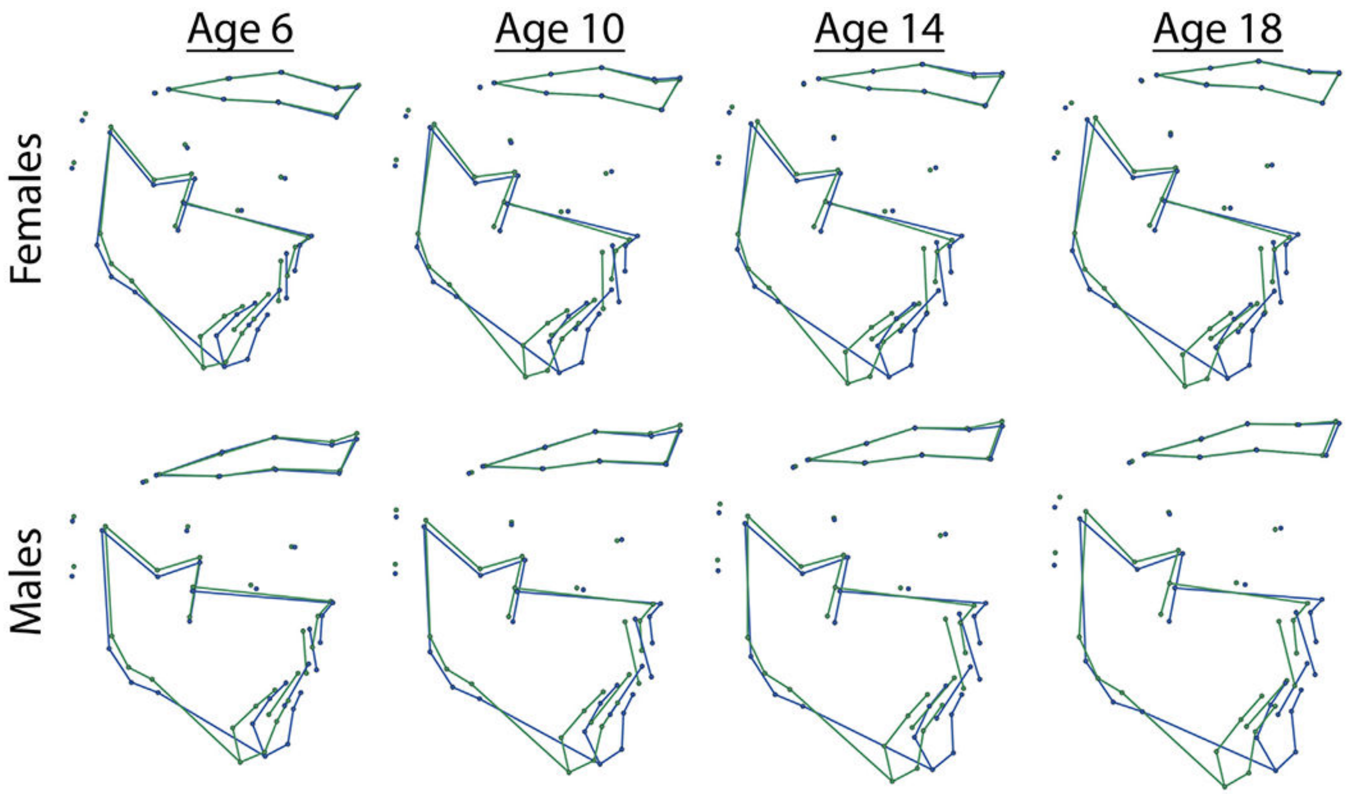

Fig 4.

Differences between the average hyperdivergent (*green*) and hypodivergent (*blue*) landmark configurations at ages 6, 10, 14, and 18 years. The landmark configurations represented by wireframe plots are the predicted configurations from the average growth trajectories depicted in Figure 2.

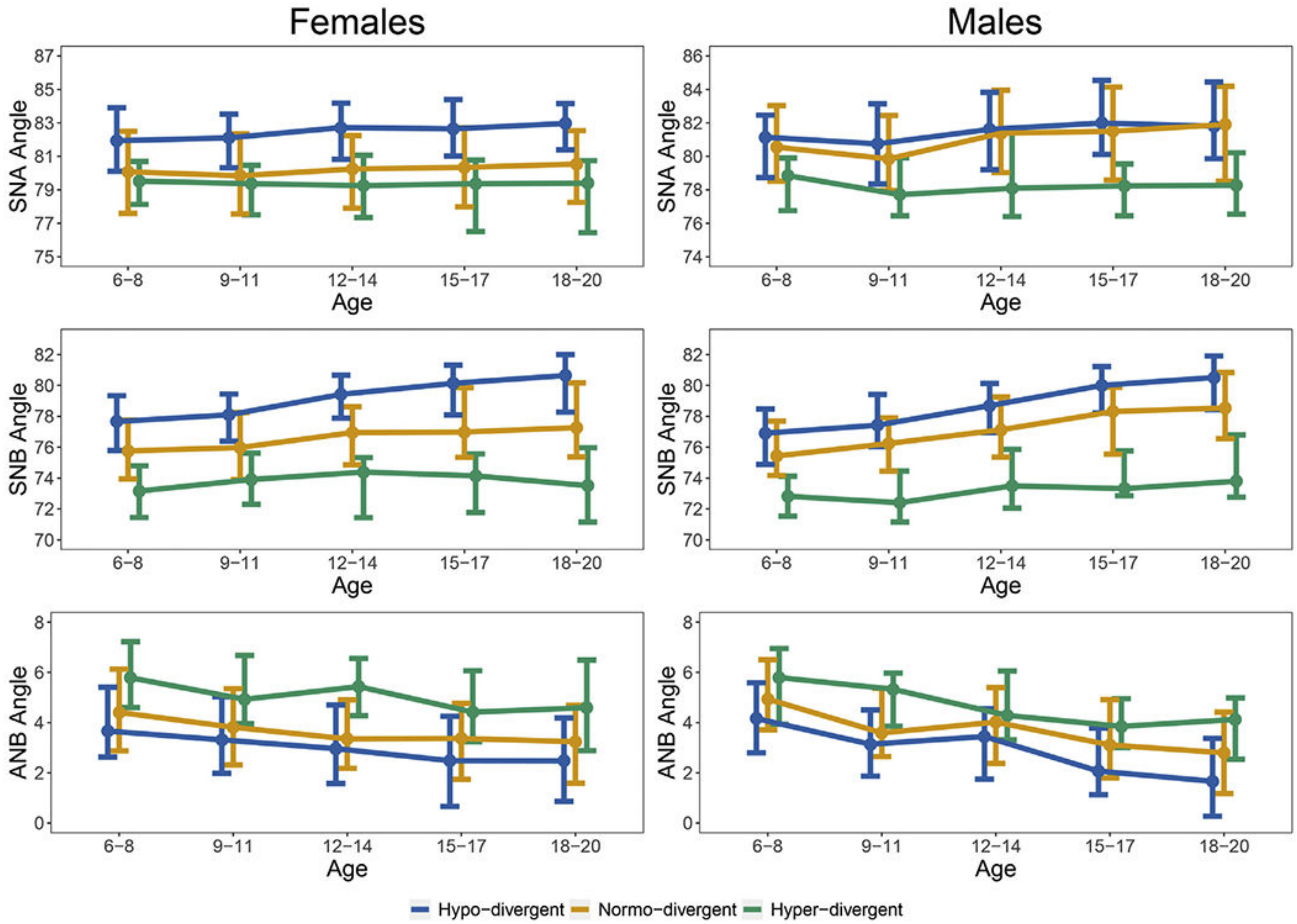

Fig 5.

Plots of SNA, SNB, and ANB angles by facial type for each age group. Points are medians and whiskers show the range for the 25th to 75th percent quantiles. *Left column*, females; *right column*, males.

Table I.

Summary of sample by sex and adult facial type classification

Classification	Females		Males	
	Participants	Cephalograms	Participants	Cephalograms
Hyperdivergent	21	105	19	95
Normodivergent	113	565	103	515
Hypodivergent	49	245	66	330
Total	183	915	188	940

Table II.

Description of landmarks collected for this study

No.	Landmark	Definition
1	SELLA	The midpoint of the pituitary fossa
2	NASION	The most anteroinferior point on the frontal bone at the nasofrontal suture
3	ORBITALE	Inferiormost point of the orbital margin of the more anterior orbital image
4	U I APEX	Point of intersection between the long axis of the more anteriorly positioned maxillary central incisor and the contour of that tooth's root-end curvature
5	POINT A	The deepest point on the curvature of the surface of the maxillary bone between ANS and the alveolar crest of the maxillary central incisor
6	U I EDGE	Tip of the incisal edge of the more anteriorly placed maxillary central incisor
7	L I EDGE	Tip of the incisal edge of the more anteriorly placed mandibular central incisor
8	POINT B	The deepest point on the curvature of the anterior border of the mandible between pogonion and the alveolar crest of the mandibular central incisor
9	L I APEX	Point of intersection between the long axis of the most anteriorly positioned mandibular incisor and the contour of that tooth's root-end curvature
10	POGONION	Anterior-most point of the bony chin at the midline
11	MENTON	Inferiormost point on the mandible at the symphysis
12	CONDYLE	The point on the posterior-superior contour of the condyle that is the longest distance from pogonion
13	PNS	The intersection between the posterior extension of the superior surface of the palate and the downward extension of the pterygomaxillary fissure
14	BASION	Inferiormost point on the anterior margin of the foramen magnum in the midsagittal plane
15	PORION	Most superior point of the external auditory meatus of the right ear
16	ANS	Anterior-most point of the anatomic anterior nasal spine
17	GLABELLA	The most anterior point on the osseous forehead
18	SE*	The midpoint between the intersections of the 2 great wings of the sphenoid bone with the sphenoid plane
19	POINT P*	Point of greatest convexity between the anterior contour of sella turcica and the sphenoid plane
20	PTM	Pterygomaxillary fissure point: the intersection of the inferior border of the foramen rotundum with the posterior wall of the pterygomaxillary fissure
21	SIGMOID	The deepest point of the sigmoid notch
22	P RAMUS	Posterior ramus point where the inflection starts
23	CORONOID	Tip of the coronoid process
24	A RAMUS	The deepest point in the anterior ramus
25	INFRADENTALE	Most superior and anterior point of the mandibular alveolar process
26	LINGUAL L1	Most superior and anterior point of alveolar bone on the lingual surface

No.	Landmark	Definition
27	LINGUAL POINT B	Intersecting point of a posterior extension of point B parallel to the mandibular plane connecting gonion and menton on the lingual cortical plate of the symphysis
28	L SYMPHY	Intersecting point of a posterior extension of pogonion parallel to the mandibular plane connecting gonion and menton on the lingual cortical plate of the symphysis
29	ANTEGONION	The deepest point of the antegonial notch
30	PROSTHION	Most inferior and anterior point of the maxillary alveolar process
31	FRONT	Point of intersection between the roof of orbit line and the internal cortical plate of the frontal bone
32	ROOF*	Most superior point of the roof of the orbit, the top point between FRONT and SE-S
33	SE-S*	Point of intersection of the greater wing of the sphenoid bone and the roof of the orbit (midpoint between 2 greater wings of the sphenoid bone)
34	ETHMOID*	Point of intersection between the lateral border of the ethmoid bone and the vertical extension of the most anteriorly positioned Key ridge
35	ZYGOMA	Most inferior point of the most anteriorly positioned key ridge
36	GONION	Average of upper and lower gonion points

*Anterior cranial base landmarks used for superimposition.

Table III.

Model comparison of the mean squared error using leave-one-out cross-validation

Classification	Linear	Second-order	Third-order	Fourth-order
Females				
Hyperdivergent	0.01048	0.01045	0.01047	0.01045
Normodivergent	0.01204	0.01198	0.01198	0.01199
Hypodivergent	0.01252	0.01241	0.01241	0.01247
Males				
Hyperdivergent	0.01107	0.01107	0.01109	0.01119
Normodivergent	0.01047	0.01039	0.01039	0.01039
Hypodivergent	0.01046	0.01041	0.01043	0.01045

Table IV.

P values from pairwise permutation tests with 10,000 iterations

Males\females	Hyperdivergent	Normodivergent	Hypodivergent
Hyperdivergent	-	0.0003	0.0001
Normodivergent	0.0001	-	0.0002
Hypodivergent	0.0001	0.0001	-

Note. Females, upper triangle; males, lower triangle.

Table V.

Results from the post-hoc Tukey's HSD tests

	Females			Males		
	Hyper-Normo	Hyper-Hypo	Normo-Hypo	Hyper-Normo	Hyper-Hypo	Normo-Hypo
6-8 y						
SNA	0.413	0.012*	0.025*	0.008*	0.004*	0.868
SNB	0.000*	0.000*	0.000*	0.003*	0.000*	0.028*
ANB	0.008*	0.004*	0.757	0.999	0.213	0.017*
9-11 y						
SNA	0.148	0.000*	0.000*	0.008*	0.001*	0.369
SNB	0.000*	0.000*	0.000*	0.000*	0.000*	0.002*
ANB	0.036*	0.049*	0.988	0.614	0.047*	0.039*
12-14 y						
SNA	0.142	0.000*	0.000*	0.005*	0.002*	0.796
SNB	0.000*	0.000*	0.000*	0.000*	0.000*	0.035*
ANB	0.000*	0.002*	0.982	0.951	0.190	0.045*
15-17 y						
SNA	0.039*	0.000*	0.000*	0.001*	0.000*	0.312
SNB	0.000*	0.000*	0.000*	0.000*	0.000*	0.003*
ANB	0.009*	0.003*	0.613	0.968	0.221	0.049*
18-20 y						
SNA	0.011*	0.000*	0.000*	0.001*	0.000*	0.528
SNB	0.000*	0.000*	0.000*	0.000*	0.000*	0.003*
ANB	0.005*	0.001*	0.423	0.770	0.051	0.016*

* Significant at 0.05 level.