치의학박사 학위논문

Differences in heritability of the craniofacial skeletal and dental characteristics between hypo- and hyper-divergent patterns using Falconer's method and principal components analysis

Falconer's method 와 주성분 분석을 이용한 수직적 골격 양상에 따른 두개안면골격과 치열의 유전율 차이에 관한 연구

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김 도 근

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ABSTRACT

Differences in heritability of the craniofacial skeletal and dental characteristics between hypo- and hyper-divergent patterns using Falconer's method and principal components analysis

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Objectives: The purpose of this study was to investigate the difference in heritability of craniofacial skeletal and dental characteristics between hypo- and hyper-divergent patterns.

Materials and Methods: 53 Korean adult monozygotic (MZ) and dizygotic (DZ) twins and their siblings were divided into a hypo-divergent group [Group 1, SN-MP<35°, 17 MZ pairs; 11 DZ and sibling (DS) pairs of the same gender] and hyper-divergent group (Group 2, SN-MP>35°, 16 MZ pairs; 9 DS pairs of the same gender). A total of 56 cephalometric variables were measured using lateral cephalograms. Craniofacial structures were divided into anteroposterior, vertical, dental, mandible, and cranial base characteristics. Falconer's method was used to calculate heritability (h^2>0.8, high). After principal components analysis (PCA), mean h^2 value of each component was calculated.

Results: Group 1 exhibited high heritability values in shape and position of the mandible, vertical angular/ratio variables, cranial base shape, and maxillary incisor inclination. Group 2 showed high heritability values in anteroposterior (AP) position of the maxilla, inter-maxillary relationship, vertical angular variables, cranial base length, and mandibular incisor inclination. Occlusal plane inclination showed high heritability in both groups. Although vertical structure presented a high overall mean h^2 value in Group 1, there were no structures that exhibited a high overall mean h^2 value in Group 2. PCA derived 10 components with 91.2% and 92.7% of cumulative explanation in Groups 1 and 2, respectively. In Group 1, three components, which depicts the vertical angular relationships and ratio, the shape of the mandible, inclination of the occlusal plane and upper incisor inclination, exhibited high mean h^2 values (PCA1, 0.891; PCA2, 1.140; PCA6, 1.325). In Group 2, three components, which depicts the AP position of the maxilla, intermaxillary relationship, lower incisor inclination, inclination of the occlusal plane and anterior cranial base length, exhibited high mean h^2 values (PCA3, 1.003; PCA9, 1.420; PCA10, 1.339).

Conclusions: It is necessary to estimate or predict growth according to vertical pattern for providing differential diagnosis and orthodontic/orthopedic treatment planning.

Key words: heritability; twins; Falconer’s method; principal components analysis; vertical pattern

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I. INTRODUCTION

Both genetic and environmental factors can contribute to variations in the size and shape of the craniofacial skeletal and dental structures. If these structures are mainly influenced by genetic factors, orthodontic and/or orthopedic treatment, performed even at an early age, would not significantly changes them. On the contrary, if these structures are under control of environmental factors, it would be advantageous to treat the patient from an early age. Therefore, it is necessary to verify the degree of genetic and environmental contributions to the characteristics of these structures for appropriate diagnosis and treatment planning.

Cephalometric studies of twins and their families can evaluate the relative contributions of genetic and environment factors on the size and shape of the craniofacial skeletal and dental structures.[1] However, whether vertical traits are more genetically determined than horizontal traits remains controversial. Several previous studies insisted that vertical measurements had greater heritability than horizontal measurements.[2-6] On the contrary, other researchers reported that genetic factors might contribute more to horizontal traits compared to vertical traits.[7, 8] However, heritability estimates should be interpreted with caution because there are possibilities for the several types of bias.[9]

Since heritability of the craniofacial characteristics can be influenced by age, sex, ethnicity, and study design, it is necessary to adopt a study design with strict sample selection criteria. For examples, the samples should be adult subjects whose growth is completed and who have the same ethnicity and sex. In addition, the samples should be divided according to the vertical and/or horizontal pattern.

Although there are some studies investigating the influences of genetic and environmental factors on the craniofacial phenotype in Korean adult twins and their siblings,[8,10] there are no twin studies comparing the heritability of the craniofacial skeletal and dental characteristics between skeletal hypo- and hyper-divergent subjects. Therefore, the purpose of this study was to investigate the differences in heritability of craniofacial skeletal and dental characteristics between hypo- and hyper-divergent patterns in monozygotic (MZ) adult twins, dizygotic (DZ) adult twins, and their adult siblings. The null hypothesis was that there was no significant difference in heritability of the craniofacial skeletal and dental characteristics between hypo- and hyper-divergent subjects.

II. REVIEW OF LITERATURE

1. Heritability

Heritability is generally defined as the proportion of phenotypic variation caused by genetic differences.[6,7] The calculation of heritability provides a means of quantifying the extent of the genetic contribution to phenotypic variation.[11]

Two types of heritability are usually considered: “broad-sense heritability” refers to additive and non-additive genetic contributions to the observed variation and “narrow-sense heritability” refers to the contribution of additive genetic variance to expressed phenotypic variance.[11] Additive genetic variance (A) denotes the variance resulting from the sum of allelic effects across multiple genes, whereas non-additive effects (D) include the effects of genetic dominance (allelic interactions within genes) and gene–gene interaction between multiple genes (epistasis).[11,12]

2. Study design for estimation of heritability using the twin and their family

The vast majority of study has employed the twin and their family to estimate the relative genetic and environmental influences on the craniofacial morphology. MZ twins share the same genes, whereas DZ twins and their siblings share only half of their genes on average.[13] MZ and DZ twins are considered to be sampled from the same gene pool and that the twins and their families are assumed to share common environmental effects.[8,10] Therefore, one can estimate the relative contributions of genetic and environmental influences to observed variation in the facial and occlusal morphology.[11]

Twin and their family studies make it possible to differentiate the observed variation of a trait into genetic (additive and non-additive), shared environmental (C), and residual variance (E).[12,14] Shared environmental variance results from environmental influences shared by family members, such as prenatal environment, residential environment, and socioeconomic status. Residual variance results from environmental influences that are not shared by family members, such as idiosyncratic experiences (like illness and injury), stochastic biological effects, and also includes measurement error.[12]

The twin study design can be extended by including additional family members (siblings, parents, offspring, and spouses). Inclusion of extra-family members increases the statistical power and makes it possible to estimate more parameters and allow less restrictive assumptions regarding assortative mating and familial transmission. In addition, the data from siblings makes it possible to test for twin-specific environmental influences.[12,15]

In the classical twin study, path analysis and Dahlberg's analysis were employed to calculate the heritability.[4] The path analysis allows a separation of genetic and environmental influences for a given trait using the path diagram and calculates the genetic heritability and cultural inheritance based on the intra-class correlation coefficient of MZ and DZ pairs.[12] Dahlberg's analysis utilizes the intra-pair variances for MZ and DZ twins to calculate the quotient between genetic and environmental standard deviations.[4]

Recently, model-fitting methods have been used to determine the relative significance of the different component of the variance.[5-7] The heritability analysis by model fitting employs maximum likelihood structural equation modeling to estimate the A, C, D, and E influences more precisely.[12] Different combinations of A, C, D, and E models are tested in a univariate way and the goodness-of-fit is evaluated to determine the model that best explains the observed variance based on the Chi-square value and Akaike information criterion.[6,7,12]

3. Falconer's method

In 1996, Falconer and Mckay[16] proposed the classical twin study design and formula to estimate the relative contribution of genetics and environment to variation in a particular trait, which are based on the difference between twin correlations (Pearson's correlation, r).

Twin correlations represent the degree of association for selected traits between pairs of related individuals, with maximum genetic correlation values that are assumed to be 1.0 for MZ twins and 0.5 for DZ twins.[11,12] Since the correlation between MZ twins (r_{mz}) and DZ twins (r_{dz}) were determined by sum of the genetic effects (A) and shared environmental effects (C), r_{mz} can be summarized as A + C and r_{dz} as $\frac{1}{2}$ A + C.[8,10,16] Solving for A and C, the genetic heritability (h^2) can be calculated as $h^2 = 2\ (r_{mz} - r_{dz})$ and the cultural inheritance (c^2) can be calculated as $c^2 = 2r_{dz} - r_{mz}$.[8,10,12,16,17] Since the classical twin design cannot differentiate the additive factors from other genetic factors, the heritability estimates refers to broad-sense heritability.[12,18]

Although Falconer's method is conceptually simple and does not require genotyping, heritability can be overestimated due to strict assumptions.[18,19] In addition, Falconer's method is not adequate for testing sex differences and multivariate data.[12,18]

The h^2 values from Falconer's method can be less than 0 or greater than 1.[4,8,19] Therefore, heritability estimates from Falconer's method shows not the percentage of genetic influences to observed variation but rather the variance of parameter which could be explained by genetic factors.[20]

4. Heritability of the vertical and horizontal craniofacial characteristics

Since the results of heritability in twin studies are difficult to compare because of the differences in zygosity determination, sample size, maturity stage, and statistical methods used, there has been inconsistency in heritability of the vertical and horizontal craniofacial traits among previous studies.[7,8,19]

According to Hunter[2] and Hunter et al.,[3] the vertical variables were more influenced by heredity than the horizontal ones. Manfredi et al.[4] studied the heritability of 39 lateral cephalometric parameters using the path analysis and Dahlberg' quotients in MZ and DZ twins and their siblings and reported that genetic control is strong especially on the vertical parameters. Among the vertical skeletal parameters, high h^2 values were found at the total anterior facial height (TAFH, 1.5) and the lower anterior facial height (LAFH, 1.56). However, the upper anterior facial height exhibited low h^2 values (UAFH, -0.36). In addition, the shape of the mandible was more genetically determined than the size of the mandible.

Savoye et al.,[5] in the twin study using the model fitting method, reported that high genetic determination was found for the vertical proportions and all the facial proportions were controlled by additive genes and specific environment. The genetic component was 71% for the upper-to-lower facial height, 66% for the anterior-to-posterior facial height, 62% for the total facial height, and 66% for the sella-A-point to sella-B-point and the sella-upper incisal edge to sella-lower incisal edge.

Carels et al.[6] also investigated the relative genetic and environmental impact on the cephalometric variables in MZ and DZ twins using the model fitting and path analysis. They found that the genetic determination is significantly higher for the vertical variables (72%) than the horizontal variables (61%). In addition, the linear craniofacial and dental measurements showed the highest genetic determination (68.2–85.8%). However, most angular measurements showed no significant genetic determination. Only the gonial angle was explained by genes for 45.3%.

In contrast, Šidlauskas et al.[7] reported higher heritability of the horizontal mandibular position than that of the vertical mandibular position using the model fitting analysis. The angular measurements representing the sagittal position of the mandible were under strong genetic influence and the shape of the mandible (gonial angle) showed a greater genetic determination than the size of the mandible (mandibular body length and ramus width).

Kim et al.[8] investigated the heritability of the skeletal and dental characteristics in Korean adult MZ and DZ twins using Falconer's method. They reported that the horizontal angular relationships between the maxilla, mandible, and anterior cranial base had a strong genetic influence. In the variables of facial vertical structures, the vertical angular relationships among the cranial base, palatal plane and mandibular plane showed a strong genetic influence. In addition, overall mean h^2 values of the facial horizontal structures were higher than that of the facial vertical structures (1.10 versus 0.71).

However, Lundström and McWilliam[21] reported no significant differences in the heritability between the horizontal and vertical measurements based on the path analysis. On average, the genetic heritability (h^2) was 0.6 for both horizontal and vertical variables, while the cultural heritability (c^2) was lower, 0.1 for the horizontal measurements and 0.2 for the vertical measurements. On the other hand, the highest h^2 values were obtained among the vertical variables and Dahlberg's analysis showed a high genetic determination of the four vertical variables in terms of the quotient between the heredity and environment.

5. Heritability of the dentoalveolar characteristics

Lundström et al.[22] investigated the relationship between genetic and non-genetic factors for six incisal position variables using the path analysis. The results were as follows: the anteroposterior apical base relationship (h^2, 0.8), lower incisor inclination (h^2, 0.7), overjet (h^2, 0.5), and upper incisor inclination (h^2, 0.4).

Kim et al.[8] reported a low heritability for the most variables of the dental structures except for SN-occlusal plane angle (h^2, 2.09) and L1-occlusal plane angle (h^2, 1.38). Amini et al.[19] also reported low-to-moderate heritability for the dental variables except for vertical dentoalveolar height of the upper molar (h^2, 0.8) and lower incisor inclination (h^2, 0.96).

However, Carels et al.[6] reported a high heritability of the vertical dento-alveolar height of the upper and lower first molars (upper first molar, 61.0%; lower first molar, 75.1%). Šidlauskas et al.[7] also reported high additive genetic determination for the sagittal position of lower incisors (84%) and chin protrusion (83%).

6. The growth pattern of hypo- and hyper-divergent subjects

Bishara et al.[23] compared longitudinal facial growth in long, average, and short facial subjects. They reported that there was a strong tendency to maintain the overall facial type as facial growth progresses with age and the differences between the three facial types in vertical relationships becomes more pronounced with age. Although the growth direction was not different among the three facial types, the overall growth amounts for the three facial types were significantly different. In addition, the subjects within each facial type expressed a relatively large variation in the size and relationships of the craniofacial skeletal and dental structures.

Nanda[24] also investigated the facial growth patterns of subjects with skeletal open bite and skeletal deep bite. Although the development of the hypo- and hyper-divergent pattern is established at an early age, these patterns seem to grow differently up to their attained mature size. The magnitude of the dimensional differences between the hypo- and hyper-divergent patterns becomes progressively accentuated during adolescence. Therefore, the relative effects of genetic and environmental factors during the craniofacial development could be different according to the vertical skeletal pattern.

Peng et al.[1] reported that vertical craniofacial characteristics appear to be strongly genetically influenced during the later stage of development, while the horizontal development by genetic factors declines as age progresses towards 12 years. In addition, various parts of the craniofacial morphology respond differently to different environmental influences.

7. Principal components analysis (PCA)

If the original data is high dimensional and of a random nature, it is difficult to interpret the patterns.[25] Therefore, it is necessary to extract the relevant information from a large dataset and to find the underlying trends with minimum loss of information.[25-27]

With PCA, we can extract a reduced number of new variables that mostly describe the variation within the original data.[25] These new variables, principal components, can be obtained from a linear combination of the original variables and they are independent of each other.[25,27] The number of principal components is determined by solving Eigenvalue problem or using iterative algorithms to estimate the principal components.[25,28]

To facilitate the interpretation of principal components, PCA often involves a rotation of the components. Varimax rotation, developed by Kaiser,[29] is the most popular rotation method. This simplifies the interpretation because, after a varimax rotation, each original variable tends to be associated with a small number of the components, and each component represents only a small number of variables.[27,29]

There have been several PCA studies to investigate the heritability of the craniofacial skeletal and dental characteristics in twins. Nakata et al.[30] found at least nine significant genetic components and eleven significant components of the environmental variation. The first five components explained 66% of the total variance and high loadings were on the all horizontal linear measurements.

However, Carels et al.[6] reported five components explaining 81% of the total variance after PCA on the craniofacial parameters. Factor 1, which explained 31% of the variance, consisted of all the horizontal variables and two of the five angular measurements. Factor 2 consisted of the vertical variables and explained 26% of the variance. Factor 3, explaining 11% of the variance, consisted of the linear measurements of the mandible and one angular measurement of the mandible. Factor 4 and factor 5 explained 8% and 5% of the variance, respectively.

According to Šidlauskas et al.,[7] PCA showed six components explaining 83% of variance. First component consisted of numerous linear variables. All angular and three linear variables were determined to components 2-5.

III. MATERIALS AND METHODS

The initial samples consisted of 150 Korean adult twins and their families (36 pairs of MZ twins, 13 pairs of DZ twins, and 26 pairs of their adult siblings), whose lateral cephalometric radiographs were taken in natural head position at Samsung Medical Center, Seoul, South Korea. This twin study protocol was reviewed and approved by the Institutional Review Board of the School of Public Health, Seoul National University, Seoul, South Korea (IRB 2005-08-113-027). Informed consent was obtained from all subjects.

The inclusion criteria were as follows:[8,10] (1) those who did not have an edentulous area of the anterior dental region that could affect the facial profile; (2) those who did not wear a removable prosthesis that could affect the vertical dimension of the face; (3) those who had not undergone orthodontic treatment or orthognathic surgery; (4) those whose growth was complete (over 19 years of age); and (5) those whose gender was the same in the DZ pairs and sibling pairs.

According to the vertical pattern, a total of 53 Korean adult twins and their siblings were allocated into the two groups (criteria: mean value of SN-MP angle of Korean adult twins, 35°; Table 1):[8] Hypo-divergent group [Group 1, SN-MP<35°; mean age, 39.0 years-old; 17 MZ pairs; 11 DZ and sibling (DS) pairs (3 DZ pairs and 8 sibling pairs)] and hyper-divergent group [Group 2, SN-MP>35°; mean age, 41.3 years-old; 16 MZ pairs; 9 DS pairs (4 DZ pairs and 5 sibling pairs)]. According to the Shapiro-Wilk normality test, the samples were normally distributed in both groups ($P>0.05$) and SN-MP angle was statistically different between the two groups (29.2 ± 3.2° vs. 41.0 ± 4.3°, $P<0.001$; Table 1).

The landmarks and reference lines used for cephalometric measurement are illustrated in Figure 1. A total of 56 linear, angular, and ratio cephalometric variables were measured using lateral cephalograms (Figure 2). The craniofacial structures were divided into five areas as follows: anteroposterior (AP), vertical, dental, mandible, and cranial base characteristics.[8] All measurements were performed by a single operator (EK) using the V-Ceph 6.0 program (Cybermed, Seoul, South Korea).

All variables from 20 randomly selected subjects were remeasured by the same operator (EK) at 2-week intervals. The intra-operator measurement error was assessed using the intraclass correlation coefficient (ICC). Since there were no significant differences between the first and second measurements, the first set of measurements was used.

Although the genetic effect (A) of the MZ pairs is equal, the DS pairs of the same gender share half of their genetics.[13] On the assumption that the MZ and DS pairs have the same environmental effect (E),[10,31] the Pearson's correlation coefficient (r_{mz}, r_{ds}) was calculated as $r_{mz}= A + E$ and $r_{ds}= \frac{1}{2} A+ E$, respectively (Table 2).

Falconer's method has been used to calculate the genetic heritability (h^2) based on the difference between the Pearson's correlation coefficients of Groups 1 and 2.[8,13,16,31,32] Heritability was calculated as $h^2 = 2 (r_{mz}- r_{ds})$.[8,10,16,32] Cultural inheritance (c^2), which shows the environmental effect, was calculated as $c^2 = 2r_{ds}-r_{mz}$.[8,10,32] In the present study, an h^2 value below 0.2 was considered low heritability and that above 0.8 was, high heritability.[8,10]

Since the degree of heritability of the variables can differ in the same craniofacial structures and the craniofacial variables are highly correlated with each other,[6] it is necessary to find the factors that account for phenotypic variance and to estimate the underlying correlations from the set of measurements. Therefore, principal components analysis (PCA) with Kaiser normalization varimax rotation was used to extract the dominant components for 56 cephalometric variables in Groups 1 and 2.[6-8,10,33,34] The components with an eigenvalue higher than 1 were selected. The mean ICC values of the cephalometric variables grouped by component were calculated. The heritability (h^2) of components was also calculated in Groups 1 and 2.

All statistical analyses were performed with a significance level of 0.05 using a SPSS program (version 21, IBM Corp., Armonk, NY, USA).

IV. RESULTS

1. Genetic Heritability (h^2) in Group 1 (Table 3)

In the AP variables, only 3 variables depicting the AP position of the mandible exhibited high h^2 values (SNB, 1.13; SN-Pog, 0.90; facial angle, 0.91). However, among the vertical variables, numerous angular variables (ODI, 1.49; SN-PP, 1.53; FH-PP, 1.29; PP-MP, 1.11) and ratio variables (N-ANS/ANS-Me, 1.09; ANS-Me/N-Me, 1.22) exhibited high h^2 values. In the dental variables, high h^2 values were observed in maxillary incisor inclination (U1-SN, 1.16; U1-FH, 1.58; U1-PP, 1.39; U1-OP, 1.04; U1-NA linear, 0.93) and occlusal plane-to-mandibular plane inclination (OP-MP, 1.29). Among the mandible and cranial base variables, high h^2 values were shown in the shape of the mandible and cranial base (gonial angle, 1.48; lower gonial angle, 1.40; saddle angle, 0.85).

2. Genetic Heritability (h^2) in Group 2 (Table 3)

Among the AP variables, the AP position of the maxilla and intermaxillary relationship exhibited high h^2 values (SNA, 1.26; convexity of A point, 1.00; ANB, 0.82; facial convexity, 1.05). The ratio between mandibular body length and anterior cranial base length also exhibited a high h^2 value (Go-Me/S-N, 0.97). However, in the vertical variables, only 4 angular variables had high h^2 values (ODI, 0.95; SN-FH, 0.88; SN-PP, 1.53; PP-MP, 1.41). Interestingly, there was no ratio variable with a high h^2 value. In the dental variables, high h^2 values were observed in mandibular incisor inclination (IMPA, 0.83; L1-NB angular, 1.18; L1-NB linear 1.14; L1-OP, 1.83), occlusal plane-to-cranial base inclination (FH-OP, 1.01) and OP-MP (0.88). Among the cranial base variables, cranial base length (Ar-N, 0.95; S-N, 1.34) exhibited a high h^2 value. However, the size and shape of the mandible did not show high h^2 values.

3. Comparison of the Overall Mean h^2 Values for the Five Structures (Table 4)

In Group 1, the overall mean h^2 value was highest at the vertical structure (0.84), followed by the dental structure (0.67), cranial base structure (0.41), mandible structure (0.39), and AP structure (0.26).

However, Group 2 did not include any structure with overall mean h^2 value greater than 0.8. The AP structure exhibited the highest value (0.66), followed by the cranial base structure (0.64), vertical structure (0.41), mandibular structure (0.26) and dental structure (0.21).

4. Principal Components Analysis (PCA) (Tables 5 to 8)

In both Groups 1 and 2, the PCA derived 10 components (Tables 5 and 6) with 91.2% and 92.7% of cumulative explanation, respectively (Tables 7 and 8).

In Group 1, three PCA components showed high h^2 values as follows: (1) PCA1 (0.891), which consisted of 5 vertical variables (SN-MP, Bjork sum, facial height ratio, FMA, PP-MP), one mandibular variable (lower gonial angle), and one dental variable (OP-MP); (2) PCA2 (1.140), which consisted of 6 dental variables (U1-NA angular, U1-FH, U1-PP, U1 to NA linear, U1-SN, U1-OP); and (3) PCA6 (1.325), which consisted of 5 vertical variables (SN-PP, N-ANS/ANS-Me, ANS-Me//N-Me, FH-PP, ODI) (Tables 5 and 7).

In Group 2, three PCA components showed high h^2 values as follows: (1) PCA3 (1.003), which consisted of 3 AP variables (Convexity of A point, ANB, Facial convexity) and 3 dental variables (L1-NB angular, L1-NB linear, IMPA); (2) PCA9 (1.420), which consisted of 2 dental variables (L1-OP, FH-OP); and (3) PCA10 (1.339), which consisted of anterior cranial base length (S-N) (Tables 6 and 8).

V. DISCUSSION

1. Comparison of the Heritability (h^2) between Groups 1 and 2 (Table 3)

Among the vertical facial variables, the angular measurements between the maxilla, mandible, and cranial base exhibited higher heritability values than the linear measurements in both groups (ODI, SN-PP, FH-PP, PP-MP in Group 1; ODI, SN-FH, SN-PP, PP-MP in Group 2). However, the vertical ratio of the anterior facial height had a strong genetic influence in Group 1 only (N-ANS/ANS-Me, ANS-Me/N-Me). These findings indicate that the relative ratio between the upper and lower anterior facial heights might be highly predictable in the hypo-divergent pattern, which was similar with the findings from Kim et al.[8] In contrast, Šidlauskas et al.[7] reported low-to-moderate genetic influence in the linear and angular vertical measurements. However, these studies[7,8] did not divide their samples according to the vertical pattern.

Interestingly, posterior facial height (S-Go) and ramus height (CD-Go, Ar-Go) did not show a high heritability in either group. These results suggested that the posterior face height demonstrated a lower genetic determination compared to the anterior face height.[7,19]

Heritability of the AP position of the maxilla and intermaxillary relationship (SNA, convexity of A point, ANB, facial convexity, Go-Me/S-N) showed a strong genetic influence in Group 2. Amini et al.[19] and Kim el al.[8] demonstrated a high heritability of the AP position of the maxilla, but a low-to-moderate heritability of the intermaxillary relationships. This difference might be due to differences in the growth stage or ethnic background of the samples.

The cranial base shape (saddle angle) showed a high heritability in Group 1, while the cranial base length (Ar-N, S-N) showed a high heritability in Group 2. Amini et al.[19]

reported a high genetic determination of anterior cranial base length and saddle angle. However, other previous studies[6, 8] reported low-to-moderate heritability values for saddle angle and cranial base length. Differences in the results might be due to the inclusion of younger twin samples before completion of growth in previous studies.[6, 19]

In the mandible characteristics, although the mandibular body length (Go-Me, Go-Pog), ramus height (CD-Go, Ar-Go) and effective mandibular length (Ar-Gn, CD-Gn) showed low-to-moderate heritability values in both Groups 1 and 2, the shape and position of the mandible (gonial angle, SNB, SN-Pog, facial angle) exhibited high h^2 values only in Group 1. These results were consistent with Amini et al.[19] and Šidlauskas et al.,[7] which reported a higher heritability of the shape and position of the mandible than its size. However, Carels et al.[6] reported a greater genetic determination for the linear measurements of the mandible compared to the angular measurements of the mandible (gonial angle, SNB). Since the influence of the environmental factors on linear mandibular measurements increases with age,[35] differences in the results might be derived from the growth stage of the samples.

The results from this study showed high heritability values of maxillary incisor inclination (U1-SN, U1-FH, U1-PP, U1-OP, U1-NA linear) in Group 1, and of mandibular incisor inclination (IMPA, L1-NB angular, L1-NB linear, L1-OP) in Group 2. Since Carels et al.[6] and Amini et al.[19] reported a high heritability of the dentoalveolar variables including mandibular incisor inclination and vertical position of the molars, the degree of dentoalveolar compensation including dentoalveolar height and incisor inclination might be significantly correlated with genetically determined skeletal parameters.

2. Comparison of the Overall Mean h^2 Values for the Five Characteristics (Table 4)

The hypo-divergent pattern had a strong genetic influence on the vertical structure, while the hyper-divergent pattern did not have strong genetic control over the vertical structures. These findings indicate that the genetic control on the vertical structure is more influential in Group 1 than in Group 2. Although, Kim et al.[8] reported highest overall mean h^2 value at the facial horizontal structures (1.10) followed by facial vertical (0.71), mandible (0.59), cranial base (0.37), and dental structures (-0.11), they did not divide their samples according to the vertical pattern.

3. Principal Components Analysis (PCA) (Tables 5 to 8)

Component number and cumulative explanation in Groups 1 and 2 were 10 components with 91.2% and 92.7%, respectively. These results were relatively higher than previous twin studies using PCA, which reported five to nine components with 81.0% to 83.0% cumulative explanation.[6, 7, 30] Differences among these studies might be derived from different study designs and different statistical criteria (i.e. eigenvalue) for determining principal components. Furthermore, those studies[6, 7, 30] did not compare the heritability values of each component between the hypo- and hyper-divergent groups.

In Group 1, the components exhibited high mean h^2 values were PCA1 (0.891), which depicts the vertical angular relationships, facial height ratio, the shape of the mandible, and inclination of the occlusal plane; PCA2 (1.140), which depicts upper incisor inclination; and PCA6 (1.325), which depicts the vertical angular relationships and anterior facial height ratio.

In Group 2, the components exhibited high mean h^2 values were PCA3 (1.003), which depicts the AP position of the maxilla, intermaxillary relationship, and lower incisor inclination; PCA9 (1.420), which depicts the inclination of the lower incisors and occlusal plane; and PCA10 (1.339), which depicts the anterior cranial base length.

These findings were similar with the result of Falconer's method and consistent with Carels et al.,[6] which reported a high additive genetic determination for the principal components depicting the vertical measurements and the shape of the mandible. However, Šidlauskas et al.[7] reported a high additive genetic determination for the components consisted of numerous linear measurements and angular relationships.

In summary, the results of the present study showed clear differences in the heritability of the craniofacial skeletal and dental characteristics between the hypo- and hyper-divergent patterns as follows (Tables 3 to 8): (1) In the vertical jaw position, the hypo-divergent pattern had strong genetic influences on both the angular and ratio measurements; while the hyper-divergent pattern, only on the angular measurements; (2) In the AP jaw position, the hypo-divergent pattern exhibited strong genetic influences only on the AP position of the mandible; while the hyper-divergent pattern, on the AP position of the maxilla and intermaxillary relationships; (3) In the size and shape of the cranial base and mandible, the hypo-divergent pattern had a strong genetic influence on the shape of both the cranial base and mandible; while the hyper-divergent pattern, only on the cranial base length; (4) In terms of incisor inclination, the hypo-divergent patterns exhibited strong genetic influences on maxillary incisor inclination; while hyper-divergent pattern, on mandibular incisor inclination; and (5) The occlusal plane inclination exhibited a high heritability in both groups.

The results of this study might reveal some clinical implications in growth modification treatment for adolescent patients. In the hypo-divergent pattern, growth modification treatment is favorable in terms of changes in mandibular length and/or AP position of the maxilla. In the hyper-divergent pattern, changing the shape and/or size of the mandible is easier compared to changing the AP position of the maxilla. However, individual responses to growth modification treatment could vary even though the structures exhibited low heritability values.

Although heritability estimates of this study might be irrelevant to a different population, the study design and results of this study might be a useful guideline to compare the heritability in different populations. This retrospective study had some limitations of study design including a relatively small sample size and two-dimensional cephalometric analysis. Therefore, three-dimensional analysis with a large sample size is necessary to investigate the heritability of transverse characteristics in future studies. In addition, further studies should be conducted to investigate the heritability of skeletal and dental characteristics according to the horizontal skeletal pattern including skeletal Cl I, Cl II, and Cl III subjects.

VI. CONCLUSIONS

- The null hypothesis was rejected.
- Since the hypo- and hyper-divergent subjects exhibited different degree of genetic influences on the AP/vertical position of the maxilla and mandible, shape of the mandible, incisor inclination, and shape and length of the cranial base, it is necessary to estimate or predict growth according to the vertical pattern for providing differential diagnosis and orthodontic/orthopedic treatment planning.

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FIGURE LEGENDS

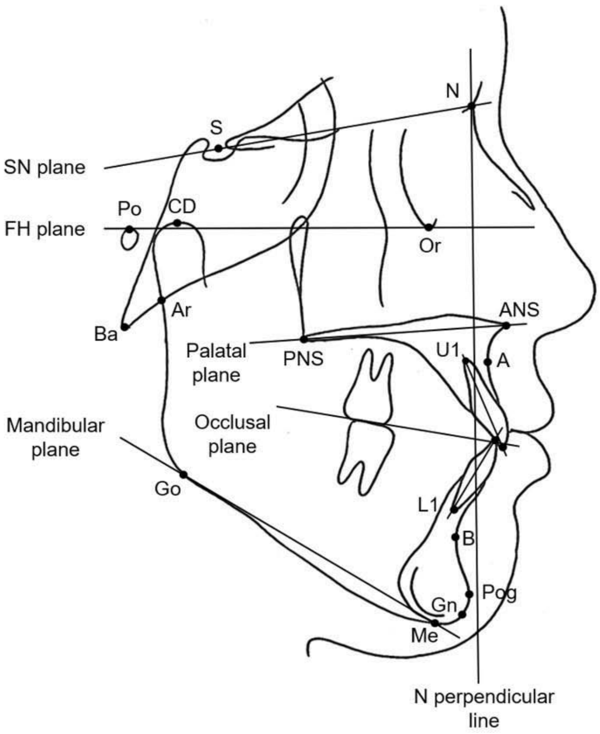

Figure 1. Landmarks and reference lines. Landmarks: S, sella; N, nasion; Po, porion; Or, orbitale; CD, condylion; Ar, articulare; Ba, basion; PNS, posterior nasal spine; ANS, anterior nasal spine; A, A point; B, B point; Pog, pogonion; Gn, gnathion; Me, menton; Go, gonion; **Reference lines:** SN plane; FH (Frankfort Horizontal) plane; Palatal plane (PP); Occlusal plane (OP); Mandibular plane (MP); N perpendicular line; U1, long axis of the upper incisor; L1, long axis of the lower incisor.

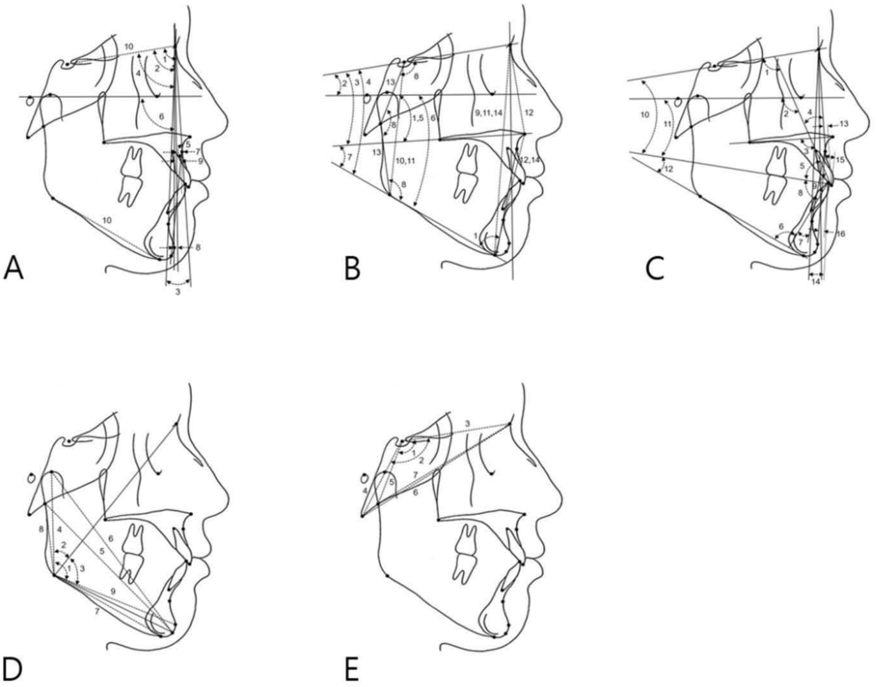

Figure 2. Cephalometric variables. A. Anteroposterior structure. 1, SNA(°), 2, SNB(°), 3, ANB(°); 4, SN-Pog(°); 5, NA-Pog(°); 6, FH-NPog(°); 7, A-N perpendicular(mm); 8, Pog-N perpendicular(mm); 9, NPog-A(mm); 10, mandibular body length/anterior cranial base(Go-Me/S-N); **B. Vertical structure.** 1, ODI(°) ; 2, SN-FH(°); 3, SN-PP(°); 4, SN-MP(°); 5, FH-PP(°); 6, FMA(°); 7, PP-MP(°); 8, Bjork Sum(°); 9, N-Me(mm); 10, S-Go(mm); 11, S-Go/N-Me; 12, N-ANS/ANS-Me; 13, Posterior cranial base/Ramus height(S-Ar/Ar-Go); 14, ANS-Me/N-Me; **C. Dental structure.** 1, U1-SN(°); 2, U1-FH(°); 3, U1-PP(°); 4, U1-NA(angular, °); 5, U1-OP(°); 6, IMPA(°); 7, L1-NB(angular, °); 8, L1-OP(°); 9, Interincisal angle(U1-L1, °); 10, SN-OP(°); 11, FH-OP(°);12, OP-MP(°); 13, U1-NA(linear, mm); 14, L1-NB(linear, mm);15, U1-APog(mm);16, L1-APog(mm); **D. Mandible structure.** 1, Gonial angle(Ar-Go-Gn, °); 2, Upper gonial angle(Ar-Go-N, °); 3, Lower gonial angle(N-Go-Gn, °); 4, CD-Go(mm); 5, Ar-Gn(mm); 6, CD-Gn(mm); 7, Go-Me(mm); 8, Ar-Go(mm); 9, Go-Pog(mm); **E. Cranial base structure.** 1, Saddle angle (N-S-Ar, °); 2, Cranial base angle(N-S-Ba, °); 3, S-N(mm); 4, S-Ba(mm); 5, S-Ar(mm); 6, N-Ba(mm); 7, Ar-N(mm).

Table 1. Demographic data of the samples

	Group 1 (Hypo-divergent group, SN-MP<35°)	Group 2 (Hyper-divergent group, SN-MP>35°)	p-value
Distribution of pairs	17 MZ pairs and 11 DS pairs (3 DZ pairs and 8 SIB pairs)	16 MZ pairs and 9 DS pairs (4 DZ pairs and 5 SIB pairs)	0.805
Gender	16 male pairs and 12 female pairs	8 male pairs and 17 female pairs	0.066
Age (years)	39.0 ± 9.8	41.3 ± 9.1	0.2582
SN-MP (°)	29.2 ± 3.2	41.0 ± 4.3	< 0.001 ***

X^2 test and Mann-Whitney U test were performed.

MZ, monozygotic twins; DS, dizygotic twins (DZ) and siblings (SIB) of the same-gender; Group 1, hypo-divergent group (SN-MP<35°); Group 2, hyper-divergent group (SN-MP>35°); ***, P<0.001.

Table 2. The effects of genetic and environmental factors on the facial horizontal, facial vertical, dental, mandible, and cranial base structures in Groups 1 and 2

Structures	Variables	Group 1 (Hypo-divergent group, SN-MP<35°)		Group 2 (Hyper-divergent group, SN-MP>35°)	
		r_{mz}	r_{ds}	r_{mz}	r_{ds}
Anteroposterior	SNA (°)	0.7510	0.6113	0.7761	0.1467
	SNB (°)	0.8530	0.2877	0.7010	0.4450
	ANB (°)	0.5370	0.9218	0.7747	0.3655
	SN-Pog (°)	0.8870	0.4356	0.7234	0.5312
	Facial convexity (NA-Pog, °)	0.6000	0.9348	0.8462	0.3188
	Facial angle (FH-NPog, °)	0.7990	0.3425	0.4862	0.3786
	A-N Perpendicular (mm)	0.4170	0.3314	0.3605	0.1101
	Pog-N Perpendicular (mm)	0.8200	0.4431	0.4233	0.4768
	Convexity of A point (NPog-A, mm)	0.6130	0.9368	0.8500	0.3494
	Mandibular body length / Anterior cranial base (Go-Me/S-N)	0.8760	0.6273	0.6546	0.1688
Vertical	ODI (°)	0.8680	0.1236	0.4796	0.0035
	SN-FH (°)	0.7580	0.5485	0.7531	0.3143
	SN-PP (°)	0.9060	0.1404	0.8388	0.0726
	SN-MP (°)	0.6880	0.4658	0.0522	0.4129
	FH-PP (°)	0.8990	0.2543	0.4168	0.5712
	FMA (°)	0.7610	0.3757	0.3367	0.4219
	PP-MP (°)	0.7660	0.2088	0.5531	-0.1544
	Bjork Sum (°)	0.6880	0.4658	0.0522	0.4129
	Ant. Facial Height (AFH, N-Me, mm)	0.9530	0.7691	0.9286	0.5563
	Post. Facial Height (PFH, S-Go, mm)	0.8900	0.6248	0.8983	0.5949
	Facial Height Ratio (S-Go/N-Me)	0.6670	0.2832	0.3861	0.3392
	N-ANS/ANS-Me	0.8630	0.3176	0.8448	0.4982
	Post cranial base / Ramus height (S-Ar/Ar-Go)	0.5560	0.4156	0.7713	0.7286
	ANS-Me/N-Me	0.8590	0.2469	0.8750	0.5642
Dental	U1-SN (°)	0.8960	0.3157	0.4524	0.7589
	U1-FH (°)	0.8820	0.0938	0.4671	0.6586
	U1-PP (°)	0.8760	0.1826	0.4651	0.7073
	U1-NA (angular, °)	0.8120	0.4403	0.6078	0.5797

Table 2. Cont'd

Dental	U1-OP (°)	0.6960	0.1778	0.1055	0.6762
	IMPA (°)	0.6600	0.6124	0.4492	0.0361
	L1-NB (angular, °)	0.7330	0.8411	0.5548	-0.0332
	L1-OP (°)	0.6610	0.6504	0.4985	-0.4152
	Interincisal angle (°)	0.9010	0.6446	0.5180	0.4810
	SN-OP (°)	0.6640	0.4120	0.4003	0.7388
	FH-OP (°)	0.5980	0.2917	0.7212	0.2153
	OP-MP (°)	0.6020	-0.0448	0.6543	0.2160
	U1-NA (linear, mm)	0.6520	0.1829	0.5928	0.6682
	L1-NB (linear, mm)	0.7880	0.8223	0.8049	0.2333
	U1-APog (mm)	0.8120	0.4855	0.5511	0.7551
	L1-APog (mm)	0.6860	0.4406	0.5289	0.4284
Mandible	Gonial angle (Ar-Go-Gn, °)	0.7110	-0.0274	0.3195	0.5230
	Upper gonial angle (Ar-Go-N, °)	0.6970	0.5739	0.7514	0.4171
	Lower gonial angle (N-Go-Gn, °)	0.7300	0.0297	0.1898	0.5829
	CD-Go (mm)	-0.0080	0.5575	0.8550	0.5521
	Ar-Gn (mm)	0.8730	0.5822	0.9690	0.7833
	CD-Gn (mm)	0.2510	0.6980	0.9467	0.7659
	Go-Me (mm)	0.9070	0.5646	0.7928	0.5566
	Ar-Go (mm)	0.7300	0.4084	0.9201	0.6411
	Go-Pog (mm)	0.7990	0.5632	0.7868	0.5562
Cranial Base	Saddle angle (N-S-Ar, °)	0.7950	0.3704	0.8518	0.6257
	Cranial base angle (N-S-Ba, °)	0.6750	0.7384	0.8179	0.5650
	S-N (mm)	0.8990	0.6089	0.8152	0.1455
	S-Ba (mm)	0.8940	0.8539	0.8382	0.7717
	S-Ar (mm)	0.8690	0.6568	0.7072	0.4913
	N-Ba (mm)	0.9310	0.7369	0.8939	0.5645
	Ar-N (mm)	0.9680	0.6212	0.8968	0.4195

r_{mz}, Pearson's correlation coefficients of the MZ group; r_{ds}, Pearson's correlation coefficients of the DZ and SIB groups.

Table 3. Genetic heritability (h^2) and cultural inheritance (c^2) of the facial horizontal, facial vertical, dental, mandible, and cranial base structures in Groups 1 and 2

Structures	Variables	Group 1 (Hypo-divergent group, SN-MP<35°)		Group 2 (Hyper-divergent group, SN-MP>35°)	
		h^2	c^2	h^2	c^2
Anteroposterior	SNA (°)	0.2794	0.4716	1.2588	-0.4827
	SNB (°)	1.1307	-0.2777	0.5120	0.1891
	ANB (°)	-0.7696	1.3066	0.8184	-0.0437
	SN-Pog (°)	0.9027	-0.0157	0.3845	0.3389
	Facial convexity (NA-Pog, °)	-0.6696	1.2696	1.0548	-0.2087
	Facial angle (FH-NPog, °)	0.9130	-0.1140	0.2151	0.2711
	A-N Perpendicular (mm)	0.1712	0.2458	0.5006	-0.1402
	Pog-N Perpendicular (mm)	0.7538	0.0662	-0.1070	0.5303
	Convexity of A point (NPog-A, mm)	-0.6476	1.2606	1.0011	-0.1511
	Mandibular body length / Anterior cranial base (Go-Me/S-N)	0.4974	0.3786	0.9716	-0.3170
Vertical	ODI (°)	1.4889	-0.6209	0.9522	-0.4726
	SN-FH (°)	0.4191	0.3389	0.8776	-0.1245
	SN-PP (°)	1.5312	-0.6252	1.5326	-0.6937
	SN-MP (°)	0.4443	0.2437	-0.7214	0.7736
	FH-PP (°)	1.2895	-0.3905	-0.3088	0.7256
	FMA (°)	0.7706	-0.0096	-0.1704	0.5071
	PP-MP (°)	1.1143	-0.3483	1.4149	-0.8618
	Bjork Sum (°)	0.4443	0.2437	-0.7214	0.7736
	Ant. Facial Height (AFH, N-Me, mm)	0.3677	0.5853	0.7446	0.1839
	Post. Facial Height (PFH, S-Go, mm)	0.5303	0.3597	0.6068	0.2915
	Facial Height Ratio (S-Go/N-Me)	0.7676	-0.1006	0.0939	0.2922
	N-ANS/ANS-Me	1.0909	-0.2279	0.6933	0.1515
	Post cranial base / Ramus height (S-Ar/Ar-Go)	0.2809	0.2751	0.0853	0.6859
	ANS-Me/N-Me	1.2241	-0.3651	0.6215	0.2535
Dental	U1-SN (°)	1.1605	-0.2645	-0.6131	1.0655
	U1-FH (°)	1.5764	-0.6944	-0.3829	0.8500
	U1-PP (°)	1.3868	-0.5108	-0.4846	0.9496

Table 3. Cont'd

Dental	U1-NA (angular, °)	0.7435	0.0685	0.0563	0.5516
	U1-OP (°)	1.0364	-0.3404	-1.1414	1.2470
	IMPA (°)	0.0952	0.5648	0.8263	-0.3771
	L1-NB (angular, °)	-0.2163	0.9493	1.1759	-0.6212
	L1-OP (°)	0.0212	0.6398	1.8275	-1.3290
	Interincisal angle (°)	0.5127	0.3883	0.0740	0.4440
	SN-OP (°)	0.5041	0.1599	-0.6770	1.0773
	FH-OP (°)	0.6126	-0.0146	1.0119	-0.2907
	OP-MP (°)	1.2937	-0.6917	0.8767	-0.2223
	U1-NA (linear, mm)	0.9381	-0.2861	-0.1507	0.7435
	L1-NB (linear, mm)	-0.0686	0.8566	1.1431	-0.3383
	U1-APog (mm)	0.6530	0.1590	-0.4079	0.9590
	L1-APog (mm)	0.4907	0.1953	0.2009	0.3280
Mandible	Gonial angle (Ar-Go-Gn, °)	1.4768	-0.7658	-0.4069	0.7265
	Upper gonial angle (Ar-Go-N, °)	0.2461	0.4509	0.6687	0.0827
	Lower gonial angle (N-Go-Gn, °)	1.4006	-0.6706	-0.7861	0.9760
	CD-Go (mm)	-1.1310	1.1230	0.6057	0.2493
	Ar-Gn (mm)	0.5815	0.2915	0.3714	0.5976
	CD-Gn (mm)	-0.8941	1.1451	0.3616	0.5851
	Go-Me (mm)	0.6849	0.2221	0.4724	0.3204
	Ar-Go (mm)	0.6432	0.0868	0.5580	0.3621
	Go-Pog (mm)	0.4716	0.3274	0.4612	0.3256
Cranial Base	Saddle angle (N-S-Ar, °)	0.8491	-0.0541	0.4523	0.3995
	Cranial base angle (N-S-Ba, °)	-0.1269	0.8019	0.5057	0.3122
	S-N (mm)	0.5802	0.3188	1.3393	-0.5242
	S-Ba (mm)	0.0801	0.8139	0.1329	0.7053
	S-Ar (mm)	0.4243	0.4447	0.4319	0.2753
	N-Ba (mm)	0.3882	0.5428	0.6589	0.2350
	Ar-N (mm)	0.6937	0.2743	0.9546	-0.0578

Table 4. Comparison of the overall mean values of genetic heritability (h^2) and cultural inheritance (c^2) for the facial horizontal, facial vertical, dental, mandible, and cranial base structures in Groups 1 and 2

Structures	Group 1 (Hypo-divergent group, SN-MP<35°)		Group 2 (Hyper-divergent group, SN-MP>35°)	
	h^2	c^2	h^2	c^2
Anteroposterior	0.2561	0.4592	0.6610	-0.0014
Vertical	0.8403	-0.0458	0.4072	0.1776
Dental	0.6713	0.0737	0.2084	0.3148
Mandible	0.3866	0.2456	0.2562	0.4695
Cranial base	0.4127	0.4489	0.6394	0.1922

Table 5. Principal components analysis (PCA) after varimax rotation in Group 1

	PCA1	PCA2	PCA3	PCA4	PCA5	PCA6	PCA7	PCA8	PCA9	PCA10
SN-MP (°)	**0.929**	-0.010	0.173	-0.274	-0.094	0.054	0.032	-0.002	-0.068	0.021
Bjork Sum (°)	**0.929**	-0.010	0.173	-0.274	-0.094	0.054	0.032	-0.002	-0.068	0.021
Facial Height Ratio (S-Go/N-Me)	**-0.900**	-0.046	-0.072	0.235	0.267	-0.011	0.043	0.004	-0.177	-0.068
FMA (°)	**0.885**	-0.039	0.194	0.251	-0.042	0.025	0.109	-0.055	-0.088	-0.239
Lower gonial angle (N-Go-Gn, °)	**0.842**	0.147	0.078	0.193	0.172	-0.099	0.052	-0.134	-0.350	0.046
PP-MP (°)	**0.770**	0.094	0.126	-0.028	-0.089	-0.567	0.093	-0.054	0.009	-0.006
OP-MP (°)	**0.715**	-0.008	0.197	0.264	0.000	-0.062	-0.237	-0.096	0.001	-0.125
U1-NA (angular, °)	-0.049	**0.927**	-0.060	-0.057	-0.025	-0.185	-0.162	-0.169	0.001	-0.025
U1-FH (°)	-0.023	**0.906**	0.104	0.051	-0.004	-0.159	-0.153	-0.067	-0.043	0.286
U1-PP (°)	0.051	**0.884**	0.156	0.239	0.027	0.219	-0.154	-0.073	-0.110	0.152
U1-NA (linear, mm)	0.044	**0.869**	0.007	-0.103	-0.043	-0.306	-0.110	-0.045	0.042	-0.210
U1-SN (°)	-0.024	**0.868**	0.119	0.358	0.025	-0.171	-0.103	-0.098	-0.055	0.124
U1-OP (°)	-0.103	**-0.864**	0.001	-0.144	0.050	0.111	-0.077	-0.052	0.136	-0.058
L1-OP (°)	0.020	-0.171	**-0.890**	0.151	0.149	0.102	0.118	0.087	-0.093	-0.049
L1-NB (angular, °)	0.245	0.264	**0.872**	-0.016	-0.106	-0.042	0.029	-0.021	-0.102	-0.001
IMPA (°)	-0.246	0.173	**0.867**	-0.252	-0.110	-0.011	0.038	-0.060	-0.029	-0.101
L1-NB (linear, mm)	0.404	0.248	**0.823**	0.057	0.112	0.003	0.073	0.094	-0.069	-0.069
Convexity of A point (NPog-A, mm)	0.331	-0.350	**0.765**	0.110	0.045	0.218	0.200	0.062	-0.039	0.174
ANB (°)	0.187	-0.391	**0.764**	0.068	-0.018	0.219	0.249	0.079	-0.062	0.194
Facial convexity (NA-Pog, °)	-0.332	0.349	**-0.761**	-0.121	-0.010	-0.229	-0.189	-0.073	0.041	-0.187
Interincisal angle (°)	-0.168	-0.660	**-0.688**	0.032	0.088	0.097	0.029	0.101	0.079	-0.023
U1-APog (mm)	0.337	0.585	**0.644**	-0.003	-0.020	-0.155	0.050	0.009	0.009	-0.078
L1-APog (mm)	0.494	0.505	**0.524**	0.088	0.080	-0.127	-0.120	0.041	-0.043	-0.197
SNB (°)	-0.081	0.241	-0.141	**0.887**	0.123	-0.143	-0.061	0.086	-0.084	0.197
SN-FH (°)	0.005	0.048	-0.048	**-0.858**	-0.079	0.043	-0.129	0.091	0.037	0.433
SNA (°)	0.047	-0.033	0.361	**0.841**	0.099	0.011	0.104	0.128	-0.116	0.301
SN-Pog (°)	-0.237	0.258	-0.235	**0.840**	0.109	-0.166	-0.041	0.090	-0.093	0.194
Cranial base angle (N-S-Ba, °)	0.010	-0.097	0.056	**-0.733**	0.043	0.225	-0.327	-0.176	-0.038	0.017
Saddle angle (N-S-Ar, °)	-0.098	-0.069	0.197	**-0.661**	0.099	0.355	0.038	-0.327	-0.232	-0.072
Ar-Gn (mm)	-0.049	0.079	-0.149	0.316	**0.851**	0.060	0.098	-0.056	0.256	0.095
Ant. Facial Height (AFH, N-Me, mm)	0.211	-0.146	0.060	0.142	**0.830**	0.035	0.345	0.177	0.155	-0.034
CD-Gn (mm)	0.222	0.137	-0.044	-0.067	**0.820**	-0.014	-0.047	0.066	0.227	0.109

Table 5. Cont'd

CD-Go (mm)	-0.075	0.054	-0.024	-0.241	**0.810**	-0.032	-0.198	0.126	0.011	0.010
Ar-Go (mm)	-0.505	0.013	-0.132	0.125	**0.790**	0.041	-0.150	-0.046	-0.134	-0.042
Post. Facial Height (PFH, S-Go, mm)	-0.450	-0.131	-0.019	0.252	**0.767**	0.008	0.276	0.138	0.001	-0.068
SN-PP (°)	0.163	-0.145	0.053	-0.327	0.000	**0.867**	-0.087	0.075	-0.104	0.035
N-ANS/ANS-Me	-0.197	-0.190	-0.055	-0.301	0.003	**0.835**	0.045	0.083	0.120	0.071
ANS-Me/N-Me	0.141	0.189	0.047	0.377	0.005	**-0.828**	-0.042	-0.086	-0.135	-0.024
FH-PP (°)	0.154	-0.178	0.090	0.378	0.065	**0.799**	0.021	-0.002	-0.131	-0.316
ODI (°)	-0.438	-0.431	0.406	-0.050	0.033	**0.611**	0.159	0.004	0.007	-0.143
Post. cranial base / Ramus height (S-Ar/Ar-Go)	0.250	-0.182	0.239	0.087	-0.315	-0.034	**0.781**	0.054	0.205	-0.033
S-Ar (mm)	-0.198	-0.206	0.157	0.204	0.417	-0.001	**0.766**	0.028	0.122	-0.097
S-Ba (mm)	-0.154	-0.323	0.057	0.116	0.504	-0.013	**0.638**	0.077	0.163	0.032
Pog-N Perpendicular (mm)	0.404	-0.116	0.119	-0.008	0.128	0.102	**0.409**	0.124	-0.219	-0.249
Upper gonial angle (Ar-Go-N, °)	0.113	0.226	-0.028	-0.106	-0.160	-0.054	0.025	**-0.892**	0.217	-0.040
Mandibular body length / Anterior cranial base (Go-Me/S-N)	0.077	0.002	0.069	0.371	0.116	0.141	0.291	**0.733**	-0.247	0.189
Gonial angle (Ar-Go-Gn, °)	0.603	0.255	0.028	0.042	-0.010	-0.101	0.050	**-0.731**	-0.059	0.000
S-N (mm)	-0.110	-0.080	-0.141	-0.082	0.334	-0.055	-0.002	-0.292	**0.839**	-0.075
N-Ba (mm)	-0.154	-0.261	-0.044	-0.223	0.511	0.025	0.252	-0.212	**0.640**	-0.025
Ar-N (mm)	-0.210	-0.190	0.055	-0.165	0.487	0.076	0.420	-0.300	**0.577**	-0.130
Go-Me (mm)	-0.023	-0.082	-0.047	0.313	0.446	0.086	0.301	0.490	**0.533**	0.140
Go-Pog (mm)	-0.163	-0.097	-0.094	0.334	0.461	0.096	0.247	0.461	**0.519**	0.124
A-N Perpendicular (mm)	0.055	0.000	0.418	0.273	0.079	0.054	0.017	0.249	-0.103	**0.784**
Facial angle (FH-NPog, °)	-0.288	0.367	-0.340	0.163	0.053	-0.160	-0.182	0.204	-0.076	**0.680**
FH-OP (°)	0.197	-0.432	-0.199	0.116	-0.066	0.137	0.405	0.205	-0.121	**-0.456**
SN-OP (°)	0.355	-0.369	-0.143	-0.380	-0.078	0.255	0.074	0.157	-0.175	**-0.389**

Table 6. Principal components analysis (PCA) after varimax rotation in Group 2

	PCA1	PCA2	PCA3	PCA4	PCA5	PCA6	PCA7	PCA8	PCA9	PCA10
U1-SN (°)	**0.906**	0.165	-0.210	-0.211	-0.101	-0.056	-0.133	0.037	-0.074	0.035
Interincisal angle (°)	**-0.905**	0.023	-0.287	-0.005	-0.016	-0.036	0.052	0.099	0.241	0.061
U1-FH (°)	**0.903**	0.119	-0.276	0.116	-0.073	-0.053	-0.105	0.181	-0.080	0.029
U1-PP (°)	**0.897**	0.211	-0.209	0.026	-0.085	-0.106	0.236	0.031	-0.058	-0.014
U1-NA (angular, °)	**0.882**	0.089	-0.381	0.158	-0.062	-0.053	-0.088	-0.058	-0.088	0.039
U1-NA (linear, mm)	**0.845**	0.187	-0.380	0.065	0.019	0.101	-0.190	-0.077	0.030	0.029
U1-APog (mm)	**0.823**	0.084	0.406	-0.091	0.163	0.009	-0.118	0.004	0.097	0.034
U1-OP (°)	**-0.791**	-0.104	-0.145	0.077	0.083	0.187	-0.029	-0.003	-0.449	0.007
L1-APog (mm)	**0.786**	0.048	0.238	-0.190	0.257	-0.055	-0.171	-0.114	-0.084	-0.007
SN-OP (°)	**-0.495**	-0.111	0.371	0.267	0.322	0.100	0.199	-0.274	0.259	-0.208
Post. Facial Height (PFH, S-Go, mm)	0.090	**0.913**	-0.038	-0.117	-0.282	0.151	-0.066	0.002	0.080	0.052
Ant. Facial Height (AFH, N-Me, mm)	0.076	**0.872**	0.015	0.108	0.287	0.313	-0.026	-0.015	0.070	0.119
CD-Go (mm)	0.175	**0.868**	0.007	-0.152	-0.072	0.069	0.122	0.065	-0.076	-0.154
Ar-Go (mm)	0.136	**0.863**	-0.234	-0.104	-0.301	-0.090	-0.002	-0.060	0.024	0.158
Ar-Gn (mm)	0.145	**0.845**	-0.355	0.005	-0.076	0.162	-0.061	0.150	-0.014	0.212
CD-Gn (mm)	0.216	**0.836**	-0.128	-0.094	0.131	0.252	0.036	0.203	-0.071	-0.031
S-Ar (mm)	-0.018	**0.656**	0.090	0.168	-0.231	0.275	-0.194	0.303	0.091	-0.181
Post. cranial base / Ramus height (S-Ar/Ar-Go)	-0.169	**-0.524**	0.342	0.232	0.214	0.267	-0.109	0.289	0.037	-0.266
Convexity of A point (NPog-A, mm)	-0.157	-0.138	**0.901**	-0.185	0.220	-0.080	0.112	-0.041	0.055	0.012
ANB (°)	-0.174	-0.167	**0.890**	-0.189	0.142	-0.051	0.082	-0.045	0.047	-0.041
Facial convexity (NA-Pog, °)	0.167	0.212	**-0.889**	0.192	-0.194	0.098	-0.121	0.026	-0.046	0.002
L1-NB (angular, °)	0.437	-0.104	**0.715**	-0.143	0.063	0.159	0.000	-0.078	-0.323	-0.147
L1-NB (linear, mm)	0.610	0.040	**0.650**	-0.218	0.256	-0.021	-0.082	-0.105	-0.044	-0.022
IMPA (°)	0.404	-0.114	**0.589**	0.119	-0.466	0.156	0.048	-0.153	-0.338	-0.103
SN-FH (°)	-0.064	-0.130	-0.158	**0.862**	0.079	0.013	0.081	0.373	-0.009	-0.017
SNA (°)	-0.045	0.159	0.424	**-0.842**	-0.080	-0.002	-0.089	0.216	0.041	-0.012
SNB (°)	0.074	0.304	-0.155	**-0.833**	-0.195	0.035	-0.162	0.282	0.013	0.016
Cranial base angle (N-S-Ba, °)	-0.073	0.057	-0.387	**0.807**	-0.154	-0.059	0.121	0.095	0.034	0.147
SN-Pog (°)	0.066	0.337	-0.263	**-0.778**	-0.265	0.084	-0.171	0.286	0.003	0.004
Saddle angle(N-S-Ar, °)	0.023	0.149	-0.348	**0.757**	-0.262	-0.123	0.029	0.141	-0.113	0.012
Ar-N (mm)	0.059	0.542	-0.179	**0.657**	-0.297	0.070	-0.017	0.127	-0.030	0.272

Table 6. Cont'd

N-Ba (mm)	-0.012	0.438	-0.176	**0.585**	-0.149	0.239	0.057	-0.038	0.094	0.548
Bjork Sum (°)	-0.057	-0.189	0.211	0.225	**0.918**	-0.040	0.045	-0.080	0.053	-0.060
SN-MP (°)	-0.057	-0.189	0.211	0.225	**0.918**	-0.040	0.045	-0.080	0.053	-0.060
Lower gonial angle (N-Go-Gn, °)	0.043	0.220	0.145	-0.295	**0.826**	-0.285	-0.072	0.001	0.135	-0.099
FMA (°)	-0.013	-0.092	0.300	-0.349	**0.807**	-0.046	-0.011	-0.316	0.055	-0.045
PP-MP (°)	0.039	-0.219	0.164	-0.181	**0.764**	0.036	-0.532	-0.059	0.015	0.026
Facial Height Ratio (S-Go/N-Me)	0.059	0.503	-0.071	-0.308	**-0.761**	-0.077	-0.078	0.007	0.055	-0.066
OP-MP (°)	0.142	0.029	-0.155	-0.146	**0.754**	0.091	-0.067	-0.117	-0.463	-0.062
Mandibular body length / Anterior cranial base (Go-Me/S-N)	-0.052	0.219	-0.190	-0.194	0.058	**0.799**	-0.134	0.268	-0.075	-0.240
Go-Me (mm)	0.017	0.431	-0.262	0.100	-0.056	**0.773**	-0.065	0.176	-0.092	0.153
Go-Pog (mm)	-0.012	0.439	-0.202	0.127	-0.136	**0.758**	-0.019	0.169	-0.105	0.195
Gonial angle (Ar-Go-Gn, °)	0.152	0.095	-0.197	-0.012	0.504	**-0.741**	-0.126	0.236	0.058	0.042
Upper gonial angle (Ar-Go-N, °)	0.156	-0.094	-0.401	0.277	-0.159	**-0.686**	-0.094	0.307	-0.059	0.152
S-Ba (mm)	-0.086	0.428	0.108	-0.059	0.011	**0.564**	-0.096	-0.030	0.215	0.292
FH-PP (°)	-0.077	0.209	0.174	-0.218	-0.022	-0.120	**0.806**	-0.365	0.052	-0.102
SN-PP (°)	-0.124	0.079	0.028	0.527	0.046	-0.099	**0.799**	-0.017	0.043	-0.108
N-ANS/ANS-Me	-0.243	-0.297	0.073	0.363	-0.114	0.124	**0.722**	0.131	-0.009	0.263
ANS-Me//N-Me	0.239	0.324	-0.109	-0.467	0.045	-0.064	**-0.696**	-0.052	0.016	-0.231
ODI (°)	-0.166	-0.013	0.474	0.072	-0.525	-0.076	**0.580**	-0.279	-0.005	-0.020
A-N Perpendicular (mm)	-0.150	0.064	0.461	-0.177	-0.024	-0.010	-0.035	**0.829**	0.052	-0.028
Pog-N Perpendicular (mm)	-0.053	-0.175	0.462	-0.060	0.243	-0.074	0.084	**-0.787**	0.041	0.051
Facial angle (FH-NPog, °)	0.005	0.251	-0.487	0.053	-0.223	0.113	-0.111	**0.757**	-0.007	-0.015
L1-OP (°)	-0.569	0.086	-0.381	-0.113	0.104	-0.014	-0.005	0.039	**0.659**	-0.014
FH-OP (°)	-0.493	-0.065	0.497	-0.223	0.023	-0.097	0.165	-0.239	**0.508**	-0.045
S-N (mm)	0.133	0.380	-0.132	0.496	-0.177	0.001	0.113	-0.132	-0.049	**0.657**

Table 7. The Pearson's correlation coefficients (r) and heritability (h^2) for each principal component in Group 1

Principal components	Variance explained (%)	Cumulative percentage (%)	r_{mz}	r_{ds}	$h^2_{(Group\ 1)}$
PCA1	14.355	14.355	0.700	0.255	**0.891**
PCA2	13.906	28.261	0.802	0.232	**1.140**
PCA3	12.635	40.896	0.699	0.729	-0.060
PCA4	10.983	51.879	0.787	0.499	0.576
PCA5	10.437	62.316	0.615	0.607	0.016
PCA6	7.782	70.099	0.879	0.217	**1.325**
PCA7	5.827	75.926	0.785	0.592	0.385
PCA8	5.612	81.537	0.761	0.391	0.740
PCA9	5.103	86.641	0.901	0.619	0.564
PCA10	4.526	91.167	0.620	0.344	0.550

$h^2_{(Group\ 1)} = 2\ (r_{mz} - r_{ds})$.

r_{mz}, Pearson's correlation coefficients of the MZ group; r_{ds}, Pearson's correlation coefficients of the DS group.

PCA1 depicts the vertical angular relationships, facial height ratio, the shape of the mandible, and inclination of the occlusal plane; PCA2 depicts upper incisor inclination; and PCA6 depicts the vertical angular relationships and anterior facial height ratio.

Table 8. The Pearson's correlation coefficients (r) and heritability (h^2) for each principal component in Group 2

Principal components	Variance explained (%)	Cumulative percentage (%)	r_{mz}	r_{ds}	$h^2_{(Group\ 2)}$
PCA1	15.679	15.679	0.469	0.645	-0.353
PCA2	13.939	29.618	0.875	0.639	0.471
PCA3	13.407	43.025	0.713	0.212	**1.003**
PCA4	12.369	55.394	0.802	0.451	0.701
PCA5	12.191	67.585	0.318	0.319	-0.002
PCA6	7.030	74.615	0.691	0.499	0.383
PCA7	6.198	80.814	0.691	0.342	0.698
PCA8	6.122	86.936	0.423	0.322	0.203
PCA9	2.999	89.935	0.610	-0.100	**1.420**
PCA10	2.747	92.681	0.815	0.145	**1.339**

$h^2_{(Group\ 2)} = 2\ (r_{mz} - r_{ds})$.

r_{mz}, Pearson's correlation coefficients of the MZ group; r_{ds}, Pearson's correlation coefficients of the DS group.

PCA3 depicts the anteroposterior position of the maxilla, intermaxillary relationship, and lower incisor inclination; PCA9 depicts the inclination of the lower incisors and occlusal plane; and PCA10 depicts the anterior cranial base length.

국문초록

Falconer’s method 와 주성분 분석을 이용한 수직적 골격 양상에 따른 두개안면골격과 치열의 유전율 차이에 관한 연구

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목적: 본 연구의 목적은 수직적 골격 양상에 따른 두개안면골격과 치열의 유전율 차이를 파악하는 것이었다.

방법: 연구대상은 한국인 성인 일란성 쌍둥이 (monozygotic twin, MZ) 와 성별이 동일한 이란성 쌍둥이 및 이들의 형제자매 (dizygotic twin and sibling, DS) 이었으며, 이들을 수직적 골격 양상에 따라 단안모 군 (hypo-divergent group, 1 군, SN-MP<35°, MZ 17 쌍; DS 11 쌍) 과 장안모 군 (hyper-divergent group, 2 군, SN-MP>35°, MZ 16 쌍; DS 9 쌍)으로 분류하였다. 측모두부계측 방사선 사진상에서 총 56 개의 변수들을 계측하였고, 두개안면구조물 (craniofacial structures)을 전후방적, 수직적, 치열, 하악골, 두개저로 나누었다. Falconer's method 를 사용하여 각 변수 및 두개안면구조물의 유전율을 계산하였고, 유전율 값이 0.8 을 초과하는 경우 높은 유전율을 갖는 것으로 판단하였다. 변수들에 대한 주성분 분석 (principal components analysis)을 통해 각 군의 특성을 나타내는 주성분들을 추출하였고, 이 주성분들의 유전율을 계산하였다.

결과: 이로부터 다음과 같은 결과를 얻었다.

1. 1 군에서는 하악골의 형태와 위치, 수직적인 각도 및 비율, 두개저의 형태, 상악전치 각도가 유전율이 높은 것으로 나타났다.
2. 2 군에서는 상악골의 전후방적인 위치, 상악골과 하악골의 악간 관계, 수직적인 각도, 두개저의 길이, 하악 전치 각도가 유전율이 높은 것으로 나타났다.
3. 교합평면의 기울기는 두 군 모두에서 유전율이 높은 것으로 나타났다.
4. 1 군에서는 두개안면구조의 수직적 계측치들에서 평균적으로 유전율이 높게 나타났지만, 2 군에서는 평균적으로 높은 유전율을 나타내는 두개안면구조가 없었다.
5. 주성분 분석에서 각 군당 10 개의 주성분들이 추출되었고, 이 주성분들이 1 군 특성의 91.2%, 2 군 특성의 92.7%를 설명하는 것으로 나타났다.
6. 1 군에서는 수직적인 각도 및 비율, 하악골의 형태, 교합평면의 기울기, 상악 전치 각도를 나타내는 3 개의 주성분들이 평균적으로 높은 유전율을 나타내었고, 2 군에서는 상악골의 전후방적인 위치, 상악골과 하악골의 악간 관계, 하악 전치 각도, 교합평면의 기울기, 전두개저의 길이를 표현하는 3 개의 주성분들이 평균적으로 높은 유전율을 나타내었다.

결론: 장안모 군과 단안모 군에서 두개안면골격 및 치열의 유전율이 서로 다르게 나타났으므로, 교정 진단과 치료 계획 수립시 수직적 골격 양상을 고려하여 성장을 평가하고 예측하는 것이 필요하다.

주요어: 유전율, 쌍둥이, Falconer's method, 주성분 분석, 수직적 골격 양상

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