Original Article

Longitudinal growth changes of the cranial base from puberty to adulthood

A comparison of different superimposition methods

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ABSTRACT

Objective: To investigate the stability of cranial reference landmarks from puberty through adulthood and to compare the displacement of these landmarks among the superimposition methods of Björk, Ricketts, Steiner, and the proposed tuberculum sella-wing (T-W) reference line.

Materials and Methods: The sample consisted of serial lateral cephalometric radiographs of 30 Class II division 1 patients taken at the pretreatment (T1; mean age, 11.98 years), posttreatment (T2; mean age, 15.32 years) and postretention (T3; mean age, 32.12 years) periods. All cephalometric radiographs were superimposed at the cranial base according to the overall superimposition methods of Björk, Ricketts, Steiner, and the T-W method. The horizontal and vertical displacements of cranial landmarks (nasion, wing, tuberculum sella, sella, basion, and pterygomaxillare) were assessed by paired *t*-test according to Björk's structural method. One-way analysis of variance (ANOVA) was used for comparison of the displacement of cranial landmarks among the superimposition methods.

Results: The tuberculum sella and wing were the most stable cranial landmarks of the cranial base. The stability of sella and pterygomaxillare points were somewhat questionable. Nasion and basion were highly variable. The displacements of all cranial landmarks were similar between the Björk and T-W methods in all study periods. Most of the cranial landmarks displaced similarly in the horizontal direction among the methods. Vertically, the behaviors of the cranial landmarks were frequently different.

Conclusions: T-W is the most similar superimposition method to Björk's structural method; thus, it is a reliable method for examining overall facial changes. (*Angle Orthod.* 2010;80:725–732.)

KEY WORDS: Cephalometrics; Superimposition methods; Cranial landmarks; Longitudinal growth

INTRODUCTION

The cranial base has long been suggested for overall facial superimposition because of its stability during the early ages of adolescence.[1–7] This view had widely been recognized in our field, but a scientific approach requires comprehensive examination of current concepts. Two basic principles should be taken into account when the development of the cranial base is evaluated: functional matrix theory[8,9] and counterpart analysis.[10] The cranial base is located between the brain and the face. Thus, it continues development according to neural (neurocranial capsule) and skeletal (orofacial capsule) demands. Neural, skeletal, and muscular factors are closely interrelated. To avoid errors, cranial base development should be addressed by this rationale.

The cranial base consists of three segments (ie, anterior cranial base, middle cranial base, and posterior cranial base). The anterior and posterior segments of the cranial base grow at the same rate as craniofacial skeletal growth; thus, development of these segments continues for many years in line with the growth of the jaws. However, the middle cranial base completes its development earlier due to the protection of the brain and other vital organs.[11–15] Thus, the stability of the middle cranial base after age 8 makes it an excellent baseline for the study of facial growth.[1–3,11–13,15] The

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Table 1. Chronologic Age and the Distribution of Patients According to Cervical Vertebral Maturation Stages[a]

		Pubertal Growth Stage			Postpubertal Growth Stage		
	Chronologic Age, Years	CS1	CS2	CS3	CS4	CS5	CS6
T1	11.98 ± 1.30	10	8	9	3	0	0
T2	15.32 ± 1.12	0	0	2	15	12	1
T3	32.12 ± 6.85	0	0	0	0	0	30

[a] CS indicates cervical stage; T1, pretreatment; T2, posttreatment; T3, postretention.

stability of the anterior (N) and posterior (Ba) borders of the cranial base[1–5,11,13,16–18] and even of S point[19–21] have been discussed, and it was shown that these points are highly variable during growth.

It has long been known that the tuberculum sella (T) and wing (W) points, located at the middle cranial base, are highly stable.[22,23] Because of this, the ethmoid triad system[16] and the cranial base triangle[20] superimposition methods were developed, but neither of them has become widely used. Information obtained from implant studies as well as from studies on human autopsy material[5,19,23] have shown that there are highly stable regions in the cranial base. Thus, the superimposition of serial head films on relatively stable anatomic structures is considered the most precise and the most reliable method for overall facial superimpositions.

Björk's structural superimposition method has been the gold standard for both overall facial and regional superimpositions. It has high validity and moderate-to-high reproducibility.[24] However, this method requires high-quality radiographs and dedication of time and effort. Although this limits the application of Björk's method, the more easily applied methods (ie, Steiner, Ricketts) have lower validity.

Today, we are using multiple superimposition techniques including Steiner, Ricketts, the ethmoid triad system, best fit, and the Björk method. This leads to chaos in the evaluation of treatment results.[25–28] To overcome this chaos, a superimposition method that is as reliable as the Björk method and as easily reproducible as the Steiner and Ricketts methods is required. Therefore, a two-step project has been planned. The first step is to investigate the stability of cranial reference landmarks from puberty to adulthood. The second step is to compare the changes of cranial reference landmarks noted by the Björk, Ricketts, and Steiner methods with the proposed tuberculum sella-wing (T-W) reference line.

MATERIALS AND METHODS

The material consisted of pretreatment (T1), posttreatment (T2), and postretention (T3) standardized lateral cephalometric radiographs of 30 Class II division 1 patients (18 girls, 12 boys) treated by the same orthodontist. The mean ages of the subjects at the start (T1) and at the end (T2) of treatment and long follow-up period (T3) were 11.98 ± 1.30, 15.32 ± 1.12, and 32.12 ± 6.85 years, respectively. The time interval between T1–T3 periods was 20.15 ± 6.73 years. Skeletal maturity of the patients was assessed by using the cervical vertebral maturation (CVM) criteria. Accordingly, 27 of 30 subjects were included in CS1–CS3 maturation stage in T1 time and CS4–CS5 maturation stage in T2 time. The maturation stage between CS1–CS3 coincides with the accelerative growth phase (pubertal growth stage), and the cervical maturation stage between CS4–CS6 indicates the decelerative growth stage (postpubertal growth stage). Consequently, the intervals between T1–T2 and T2–T3 periods are considered as pubertal and postpubertal growth stages, respectively. The distribution of the patients according to chronologic age and cervical maturation stages is indicated in Table 1.

All cephalometric radiographs were traced and superimposed by one operator. To avoid errors in landmark identification, a template with all six landmarks (nasion, wing, tuberculum sella, sella, basion, and pterygomaxillare) was prepared for T1, T2, and T3 radiographs. This template was used for landmark identification in all superimpositions. Therefore, errors that could be due to landmark identification were eliminated. Then, all radiographs were superimposed at the cranial base according to the most commonly used superimposition methods and the newly suggested T-W method.

The stability of cranial landmarks was evaluated by using Björk's structural method. Besides, the degree of stability of the cranial landmarks was scored from 0 to 6 in consideration of the directions (horizontal and vertical) and the study periods (T1–T2, T2–T3, T1–T3). The stability score and percentage of points found stable at both directions and in all study periods were reported as 6 and 100%, respectively. However, for the points that were found stable neither at the sagittal nor at the vertical direction along the study, the stability score and rate were indicated as 0 and 0%.

A brief explanation of the superimposition methods follows.

Björk's Structural Method

The two radiographs were superimposed on the reference bony structures in the anterior cranial base as described by Björk and Skieller.[7] These anatomical reference structures are (1) the contour of the anterior wall of sella turcica, (2) the anterior contour of the median cranial fossa, (3) the mean intersection point of the lower contours of the anterior clinoid processes and the contour of the anterior wall of the sella, (4) the inner surface of the frontal bone, (5) the contour of the cribriform plate, (6) the contours of the bilateral frontoethmoidal crests, and (7) the contour of the median border of the cerebral surfaces of the orbital roofs.

Steiner (S-N Line)

The two tracings were superimposed on the S-N line with registration at S point.

Ricketts (N-Ba Line)

The two tracings were superimposed on the Ba-N line with registration at CC point (the point where the Ba-N plane and the Ptm-gnathion line intersect).

T-W Method

The two tracings were superimposed on the T-W reference line with registration at T point.

During the superimposition of the craniofacial structures, the N and S points were transferred from the first film (T1) to the second (T2) and third film (T3) to serve as fiducial reference points, and the horizontal (x) and vertical reference planes (y) were constructed using these fixed registration points. The projected distances between the landmarks and reference planes (x, y) were manually measured using a digital caliper. The differences between the first and second measurements (T1–T2), the second and third measurements (T2–T3), and the first and third measurements (T1–T3) were recorded as the amount of displacement of the landmarks (Figure 1).

Statistical Method

Paired *t*-test was used to assess the amount of displacement of cranial landmarks according to the Björk method during pubertal (T1–T2), postpubertal (T2–T3), and over all (T1–T3) study periods. One-way analysis of variance (ANOVA) and Bonferroni test were used for comparison of the displacement of cranial landmarks according to Björk, T-W, Ricketts, and Steiner methods in all study periods.

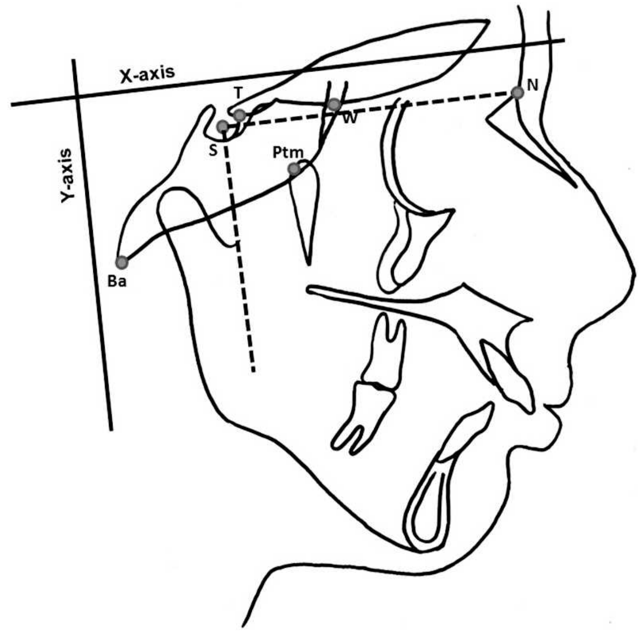

Figure 1. Cranial reference landmarks used in this study. N indicates nasion; W, wing point (the intersection of the contour of the ala major with the jugum sphenoidale); T, tuberculum sella (the intersection point of the lower contours of the anterior clinoid processes and the contour of the anterior wall of the sella); S, sella; Ba, basion; and Ptm, pterygomaxillare.

Method Error

All procedures were repeated for 10 patients by the same orthodontist 1 month later. The reliability of measurements was calculated by the Cronbach alpha reliability test. Reliability coefficient (0.942–0.999) was found to yield sufficient reliability.

RESULTS

The Stability of Cranial Landmarks

The results of paired *t*-test revealed that forward movement of N and backward movement of Ba were statistically significant in all study periods. N point also showed a downward displacement ($P < .01$) during puberty and the long follow-up period. Downward displacement of Ba was statistically significant in all study periods. T point remained stable along the study periods in both vertical and horizontal directions. W point was found stable horizontally throughout all study periods and vertically in the pubertal and long follow-up periods. In the postpubertal period, however, the downward displacement (0.29 mm) of this point was significant ($P < .05$). S point was stable in the horizontal direction through pubertal and postpubertal periods; however, in the long follow-up period, backward displacement of this point was significant ($P < .01$). In the vertical direction, S point displaced

Table 2a. Horizontal and Vertical Distances (in mm) of the Cranial Landmarks to the Reference Lines (X, Y) According to the Björk Method in the Pretreatment (T1), Posttreatment (T2), and Postretention (T3) Periods

		T1	T2	T3	Paired *t*-Test		
		Mean ± SD	Mean ± SD	Mean ± SD	T1–T2	T2–T3	T1–T3
Nasion	Horizontal	102.75 ± 6.05	104.59 ± 5.84	106.41 ± 5.97	***	***	***
	Vertical	24.97 ± 0.13	26.18 ± 2.14	26.37 ± 2.39	**	NS	**
Wings	Horizontal	56.32 ± 3.94	56.46 ± 4.09	56.33 ± 4.08	NS	NS	NS
	Vertical	25.77 ± 1.86	25.95 ± 2.08	25.65 ± 2.01	NS	*	NS
Tuberculum sella	Horizontal	35.88 ± 3.39	35.82 ± 3.46	36.01 ± 3.64	NS	NS	NS
	Vertical	23.81 ± 0.99	23.94 ± 1.17	23.70 ± 1.01	NS	NS	NS
Sella	Horizontal	31.21 ± 3.18	30.99 ± 3.39	30.70 ± 3.36	NS	NS	**
	Vertical	25.01 ± 0.09	25.32 ± 0.65	25.37 ± 0.67	*	NS	**
Pterygomaxillare	Horizontal	46.36 ± 3.62	46.62 ± 3.83	46.40 ± 3.74	NS	NS	NS
	Vertical	39.79 ± 3.31	40.41 ± 2.97	41.39 ± 2.94	NS	*	**
Basion	Horizontal	5.99 ± 2.28	4.63 ± 1.95	3.58 ± 1.68	***	**	***
	Vertical	58.75 ± 3.56	59.70 ± 3.39	61.42 ± 4.43	**	***	***

* $P < .05$; ** $P < .01$; *** $P < .001$; NS indicates nonsignificant.

downward both in the pubertal ($P < .05$) and long follow-up periods ($P < .01$) (Table 2a,b).

Comparison of the Methods

The results of variance analysis and Bonferroni tests are shown in Figure 2a through f and Tables 3 through 5. Table cells with bold font indicate the values most similar to the Björk method. Accordingly, the T-W method was the most similar to Björk's superimposition method both in horizontal and vertical directions during puberty (T1–T2) and in the long follow-up period (T1–T3) (Tables 3 and 5). In the pubertal growth stage (T1–T2), the horizontal displacement of N and Ba points was similar among the methods. In this stage of growth, vertical displacement of all cranial landmarks (N, W, T, and S) except Ptm and Ba showed statistically significant differences between the Björk-Ricketts and T-W-Ricketts methods (Table 3). In the vertical direction, however, the displacement of all cranial landmarks except Ptm and Ba was different between the Björk-Ricketts ($P < .001$), T-W-Ricketts ($P < .05$), and Steiner-Ricketts ($P < .001$) methods (Table 4). During the long follow-up period (T1–T3), vertical displacement of all landmarks except Ba showed statistically significant differences between Björk-Ricketts and T-W-Ricketts methods (Table 5).

Table 2b. The Stability Scores of the Cranial Landmarks According to the Björk Method in Both Directions and Along the Study Periods (T1–T2, T2–T3, T1–T3)

Landmark	Stability Score (0–6)	Percent
Tuberculum sella	6	100
Wings	5	83
Pterygomaxillare	4	66
Sella	3	50
Nasion	1	16
Basion	0	0

DISCUSSION

There are various error sources in cephalometric superimposition.[29–33] Some of them are inherent and unavoidable, but there are also error sources that can be overcome. These include the selection of stable reference landmarks to be used and standardization of calibration.

The Stability of Cranial Base Landmarks

The results of the study indicated that T point is the most stable (100%) landmark in both directions and through all stages. This is followed by W point with 83% stability. W and Ptm points located in the middle cranial base remained constant in the horizontal direction in all study periods. However, W point in the postpubertal period (0.29 mm, $P < .05$) and Ptm both in the postpubertal (0.98 mm, $P < .05$) and long follow-up (1.60 mm, $P < .01$) periods were displaced downwards. This vertical displacement decreased stability of Ptm (66%). Displacements shown during pubertal and long follow-up periods decreased stability of S point by 50% (Table 2b).

W point represents the anterior outline of the middle cranial fossa and is based on the morphology of neural tissues.[13] The stability of this landmark in the horizontal direction has been indicated by longitudinal cephalometric studies[13,15] and in dry skulls.[13,15] Knott[12] indicated that the distance between point W and the pituitary point increased 0.1 mm between the ages of 6 and 9 years and remains completely stable from 9 to 15 years of age. Similarly, Arat et al.[18] recently showed the T-W distance remained stable in all stages of puberty. As mentioned above, in the current study point W remained constant in the horizontal direction in all of the study periods; however, it moved slightly (0.29 mm, $P < .05$) downward only in one stage (T2–

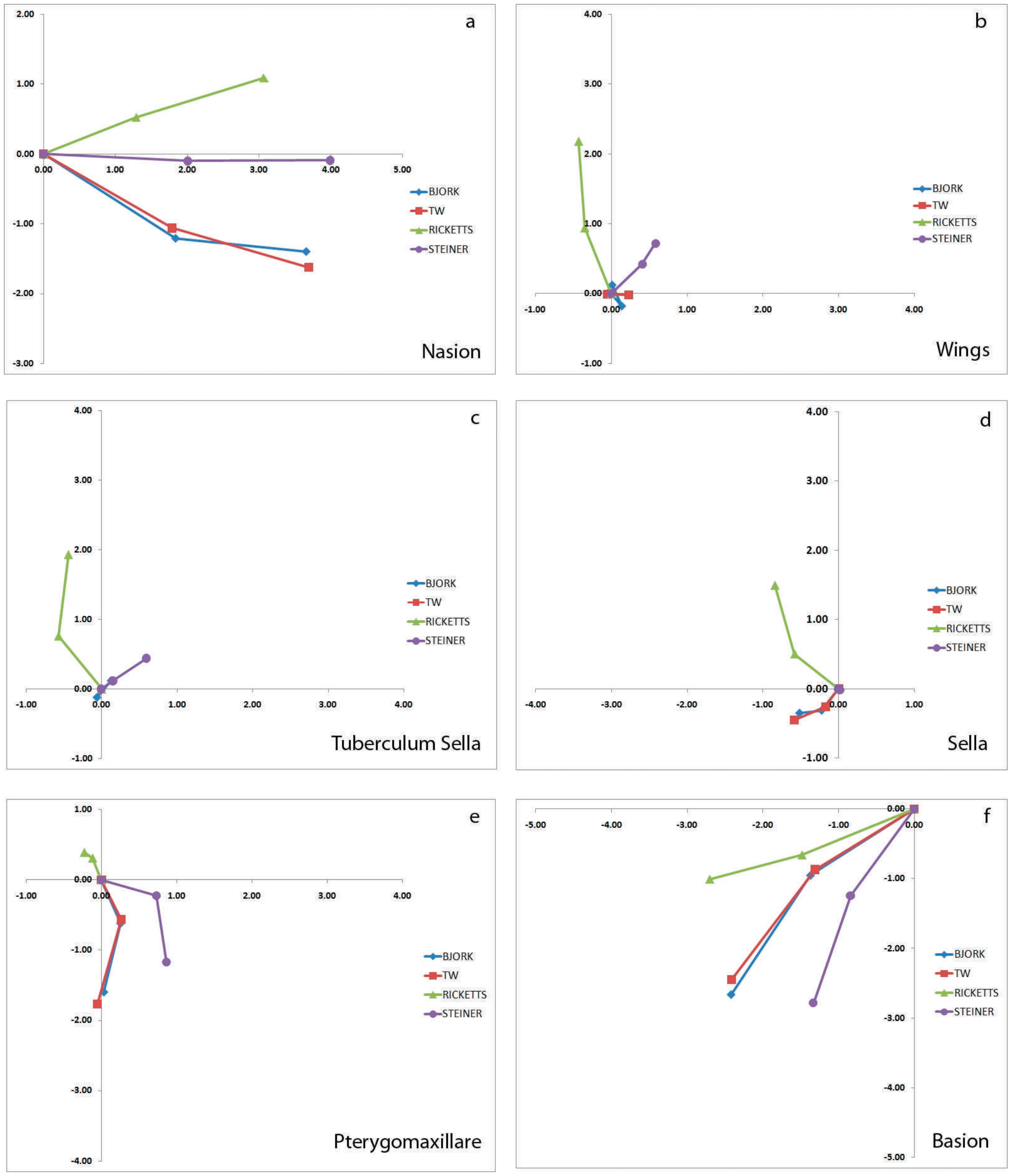

Figure 2. The graphical presentation of the displacements (in mm) of cranial reference landmarks according to the superimposition methods along the study periods: (a) nasion, (b) wings, (c) tuberculum sella, (d) sella, (e) pterygomaxillare, and (f) basion.

T3) of the study. Here, the relationship existing between the development of the brain and the cranial base must again be remembered. As reported by Enlow,[10] development of the cranial base is not solely based on sutural and synchondrosis activity. To accommodate brain expansion, growth of the endocranial fossa was accomplished by direct cortical drift, involving deposition on the outside, with resorption from the inside. This view explains the reason for vertical displacement of the cranial base landmarks. However, this does not reduce stability of W point.

The results of the present study indicated that W point is sufficiently stable (83%) (Table 2b). Moreover, it was reported that reliability of W point is high, and reproducibility is moderate to high.[13,24] In this case, it was concluded that T and W points can be used in overall superimpositions representing the middle cranial base.

The results also indicated that Ba is the most variable landmark of the cranial base (0%). This was followed by N point with 16% stability (Table 2b). It has been known that development of Ba and N continues for many years due to spheno-occipital synchondrosis on one side and development of the frontal sinus on the other side. This study also showed this finding. Therefore, the contradiction arising from superimposi-

Table 3. The Comparison of Displacement (in mm) of the Cranial Landmarks Among Björk, T-W, Ricketts, and Steiner Methods in the Pubertal Period (T1–T2)[a,b]

		Björk (I)	T-W (II)	Ricketts (III)	Steiner (IV)	ANOVA	Bonferroni Test					
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Sig	I-II	II-III	III-IV	I-III	I-IV	II-IV
Nasion	Horizontal	1.84 ± 1.51	**1.79** ± **1.71**	1.29 ± 1.82	2.01 ± 1.82	NS	NS	NS	NS	NS	NS	NS
	Vertical	1.21 ± 2.15	**1.06** ± **2.29**	−0.52 ± 0.62	0.10 ± 0.18	***	NS	**	NS	**	**	NS
Wings	Horizontal	0.14 ± 0.89	**0.23** ± **0.91**	−0.35 ± 1.34	0.41 ± 0.87	*	NS	NS	*	NS	NS	NS
	Vertical	0.18 ± 0.80	**0.02** ± **0.17**	−0.94 ± 1.10	−0.42 ± 0.66	***	NS	**	NS	**	**	NS
Tuberculum sella	Horizontal	−0.06 ± 0.69	**-0.01** ± **0.06**	−0.57 ± 1.14	0.15 ± 0.52	**	NS	**	**	**	NS	NS
	Vertical	0.12 ± 0.78	**0.01** ± **0.04**	−0.76 ± 1.32	−0.12 ± 0.65	***	NS	**	**	**	NS	NS
Sella	Horizontal	−0.22 ± 0.72	**−0.17** ± **0.53**	−0.58 ± 1.14	0.01 ± 0.03	*	NS	NS	*	NS	NS	NS
	Vertical	0.31 ± 0.64	**0.26** ± **0.76**	−0.50 ± 1.41	0.01 ± 0.06	**	NS	**	NS	**	NS	NS
Pterygo-maxillare	Horizontal	0.26 ± 1.02	**0.26** ± **1.08**	−0.12 ± 0.49	0.73 ± 0.97	**	NS	NS	**	NS	NS	NS
	Vertical	0.62 ± 1.78	**0.56** ± **1.67**	−0.31 ± 1.47	0.22 ± 1.66	NS	NS	NS	NS	NS	NS	NS
Basion	Horizontal	−1.37 ± 1.63	**−1.31** ± **1.82**	−1.48 ± 1.76	−0.84 ± 1.38	NS	NS	NS	NS	NS	NS	NS
	Vertical	0.95 ± 1.78	**0.87** ± **2.64**	0.66 ± 0.65	1.24 ± 2.19	NS	NS	NS	NS	NS	NS	NS

[a] T-W indicates tuberculum sella-wing; ANOVA, analysis of variance; Sig, significance.
[b] Bold data indicate the most similar value to the Björk method.
* $P < .05$; ** $P < .01$; *** $P < .001$. NS indicates nonsignificant.

tion methods based on N and Ba points has become definite.

Comparison of the Methods

According to the results of variance analysis, displacements of all examined cranial landmarks were similar between the Björk and T-W methods in both directions and at all study periods (Figure 2a through f; Tables 3 through 5). In fact, the T-W method had reduced the anatomy of the cranial base to a reference line passing through the most stable two points of the middle cranial base. Thus, it can be suggested that the T-W method can replace the Björk superimposition method.

The horizontal displacements of all cranial landmarks were also similar between the Björk and Steiner methods. In the vertical direction, however, the displacement of N both in the pubertal and long follow-up periods differs ($P < .01$) between the Björk and Steiner methods. This difference is due to the fact that downward displacement of N point is masked in the Steiner method. Regardless of the reason, the difference between the Björk and Steiner methods may cause variations when vertical facial changes are measured. That is, in the Steiner superimposition method, facial landmarks were displaced upward more than they would in the Björk method. This creates confusion in the interpretation, particularly of responses to functional/orthopedic interventions.[27,28]

The horizontal displacements of all cranial landmarks, except T point in the pubertal stage, were similar between Björk-Ricketts and T-W-Ricketts methods in all study periods. Vertically, however, most of the cranial landmarks displaced differently in the Ricketts method compared to both the Björk and the T-W methods

Table 4. The Comparison of Displacement (in mm) of the Cranial Landmarks Among the Björk, T-W, Ricketts, and Steiner Methods in the Postpubertal Period (T2–T3)[a,b]

		Björk (I)	T-W (II)	Ricketts (III)	Steiner (IV)	ANOVA	Bonferroni Test					
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Sig	I-II	II-III	III-IV	I-III	I-IV	II-IV
Nasion	Horizontal	1.82 ± 1.66	1.90 ± 1.82	**1.79** ± **2.00**	1.98 ± 2.09	NS	NS	NS	NS	NS	NS	NS
	Vertical	0.19 ± 2.18	0.56 ± 1.92	−0.57 ± 0.73	**−0.01** ± **0.16**	*	NS	*	NS	NS	NS	NS
Wings	Horizontal	−0.13 ± 1.06	−0.28 ± 0.73	**−0.08** ± **1.32**	0.17 ± 0.90	NS	NS	NS	NS	NS	NS	NS
	Vertical	−0.29 ± 0.72	−0.01 ± 0.18	−1.24 ± 1.26	**−0.30** ± **0.55**	***	NS	*	*	*	NS	NS
Tuberculum sella	Horizontal	0.19 ± 0.99	0.01 ± 0.06	**0.13** ± **1.16**	0.44 ± 0.40	NS	NS	NS	NS	NS	NS	NS
	Vertical	−0.24 ± 0.82	0.00 ± 0.02	−1.17 ± 1.61	**−0.33** ± **0.77**	***	NS	*	*	*	NS	NS
Sella	Horizontal	−0.29 ± 0.94	−0.41 ± 0.48	**−0.27** ± **1.19**	0.01 ± 0.10	NS	NS	NS	NS	NS	NS	NS
	Vertical	0.05 ± 0.84	0.18 ± 0.80	−0.99 ± 1.35	**0.01** ± **0.11**	***	NS	*	*	NS	NS	NS
Pterygomaxillare	Horizontal	−0.22 ± 1.23	**−0.31** ± **1.11**	−0.11 ± 0.59	0.13 ± 1.03	NS	NS	NS	NS	NS	NS	NS
	Vertical	0.98 ± 2.29	1.20 ± 2.22	−0.08 ± 1.62	**0.96** ± **2.15**	NS	NS	NS	NS	NS	NS	NS
Basion	Horizontal	−1.05 ± 1.78	**−1.10** ± **2.03**	−1.22 ± 1.98	−0.50 ± 1.81	NS	NS	NS	NS	NS	NS	NS
	Vertical	1.71 ± 2.37	**1.57** ± **2.84**	0.34 ± 0.71	1.54 ± 1.99	NS	NS	NS	NS	NS	NS	NS

[a] T-W indicates tuberculum sella-wing; ANOVA, analysis of variance; Sig, significance.
[b] Bold data indicate the most similar value to the Björk method.
* $P < .05$; *** $P < .001$. NS indicates nonsignificant.

Table 5. The Comparison of Displacement (in mm) of the Cranial Landmarks Among the Björk, T-W, Ricketts, and Steiner Methods in All Periods (T1–T3)[a,b]

		Björk (I)	T-W (II)	Ricketts (III)	Steiner (IV)	ANOVA	Bonferroni Test					
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Sig	I-II	II-III	III-IV	I-III	I-IV	II-IV
Nasion	Horizontal	3.66 ± 2.53	**3.69 ± 3.02**	3.07 ± 2.69	3.99 ± 2.97	ns	NS	NS	NS	NS	NS	NS
	Vertical	1.40 ± 2.41	**1.62 ± 2.80**	−1.09 ± 0.83	0.09 ± 0.15	***	NS	*	NS	*	*	*
Wings	Horizontal	0.01 ± 1.18	**−0.05 ± 1.12**	−0.43 ± 1.57	0.58 ± 0.97	*	NS	NS	*	NS	NS	NS
	Vertical	−0.12 ± 0.75	**0.01 ± 0.17**	−2.18 ± 1.55	−0.72 ± 0.87	***	NS	*	*	*	NS	*
Tuberculum sella	Horizontal	0.13 ± 0.83	**0.00 ± 0.00**	−0.44 ± 1.47	0.59 ± 0.49	***	NS	NS	*	NS	NS	NS
	Vertical	−0.12 ± 0.76	**0.01 ± 0.04**	−1.93 ± 1.94	−0.44 ± 0.68	***	NS	*	*	*	NS	NS
Sella	Horizontal	−0.51 ± 0.77	**−0.58 ± 0.54**	−0.84 ± 1.53	0.02 ± 0.09	**	NS	NS	*	NS	NS	NS
	Vertical	0.35 ± 0.66	**0.45 ± 0.72**	−1.49 ± 2.00	0.02 ± 0.09	***	NS	*	*	*	NS	NS
Pterygo-maxillare	Horizontal	0.03 ± 1.35	**−0.05 ± 1.46**	−0.23 ± 0.67	0.86 ± 1.40	**	NS	NS	*	NS	NS	*
	Vertical	1.60 ± 2.70	**1.77 ± 2.52**	−0.39 ± 2.05	1.17 ± 2.51	**	NS	*	NS	*	NS	NS
Basion	Horizontal	−2.41 ± 2.41	**−2.41 ± 2.53**	−2.70 ± 2.60	−1.33 ± 2.05	ns	NS	NS	NS	NS	NS	NS
	Vertical	2.66 ± 2.67	2.45 ± 3.62	1.01 ± 0.93	**2.78 ± 3.07**	ns	NS	NS	NS	NS	NS	NS

[a] T-W indicates tuberculum sella-wing; ANOVA, analysis of variance; Sig, significance.
[b] Bold data indicate the most similar value to the Björk method.
* $P < .05$; ** $P < .01$; *** $P < .001$. NS indicates nonsignificant.

through all study periods. The different behaviors of the cranial landmarks, particularly of N, would conceal the changes of the face in the vertical direction.[17,33]

The results of this study indicate that the T-W method is as reliable as Björk's structural superimposition method and is easily applied. Therefore, this study has encouraged us to propose the T-W superimposition method for examining overall facial changes both in the active growth period and in the long follow-up periods.

CONCLUSIONS

- Among the landmarks investigated in this study, T and W points were the most stable points of the cranial base.
- Superimposition at T point along the T-W line was a reliable method when examining the overall facial changes both in the active growth and long follow-up periods.
- N and Ba points were the most variable points both in the horizontal and vertical directions along all study periods. The stability of S and Ptm points was somewhat questionable, especially in the long follow-up period. This devaluates the reliability of the superimposition methods depending on those points in the studies of longitudinal basis.
- The behavior of the cranial landmarks differed among the superimposition methods. The differences were more prominent in the vertical direction.
- T-W was the superimposition method most similar to Björk's structural method in both directions along the study.

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