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Craniofacial reference plane variation and natural head position

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SUMMARY Commonly used craniofacial reference planes such as Frankfort Horizontal (FH) and sella–nasion have shortcomings, including their variable interindividual orientation when related to true horizontal (HOR). Therefore, the aim of this study was to evaluate the potential usefulness of a range of craniofacial reference planes to HOR, including those which have not been investigated previously: the Krogman–Walker (KW) line, the neutral horizontal axis, the foramen magnum line, and the posterior maxillary plane. A sample of 57 (38 female, 19 males) consecutive, pre-treatment orthodontic subjects aged 12–18 years were photographically recorded in a standing mirror-guided natural head position (NHP). Cephalograms taken at the same time were traced, orientated to a plumb line (true vertical) transferred from the photograph, and measured. Descriptive statistical analysis including means and standard deviations (SDs) were used to describe average orientation and variability. Thirty-nine of these subjects were photographically recorded 2 months later to test the reproducibility of NHP.

The results showed that the variability of the 11 selected craniofacial reference planes related to HOR was generally high. The planes illustrating the lowest variability to HOR were FH and the KW line with SDs of 4.6 and 4.7 degrees, respectively. These, however, showed approximately double the variation in NHP reproducibility (mean square error 2.1 degree). The KW line and palatal plane were also on average orientated closest to HOR. Therefore, the KW line and palatal plane are potential substitutes for the commonly used reference planes in the absence of a reliable NHP. However, NHP still represents a more valid craniofacial reference system than the investigated reference planes.

Introduction

Contemporary cephalometric analysis in orthodontics is based on comparing elements of craniofacial morphology to selected reference planes. Ideally, a valid cephalometric reference plane/system should have the following features: good reliability (low method error), good intraindividual reproducibility, low interindividual variability, and average orientation close to true horizontal (HOR) or vertical (VER).

A commonly used craniofacial reference plane is sella–nasion, SN (Broadbent, 1931). While this plane is reliable and, by representing the anterior cranial base, is biologically meaningful, it has been illustrated to have large interindividual standard deviations (SDs) when related to VER (Table 1). Therefore, due to this high interindividual variability and its 2- to 9-degree average orientation from HOR, the use of SN as a plane of reference has questionable validity.

Another reference plane in widespread use is Frankfort Horizontal (FH) as it may produce the most acceptable estimation of HOR (Moorrees and Kean, 1958). However, others (Table 1) have shown that FH not only displays large variability to VER (SD) but is also orientated on average 1–5 degrees from HOR. Another shortcoming of FH is the suggestion of its inferior reliability compared with that of SN (Lundström *et al.*, 1995) and thus the validity of using FH as a craniofacial reference plane is also questionable.

Natural head position (NHP) was introduced into orthodontics in the late 1950s (Downs, 1956; Bjern, 1957; Moorrees and Kean, 1958). Broca (1862) defined this head position as 'when man is standing and his visual axis is horizontal, he is in the natural position' (cited by Moorees and Kean, 1958). A typical method of registering NHP is based on the work of Solow and Tallgren (1971), who cited Mølhave (1958) in which subjects are asked to stand in an 'orthoposition' and look into their own eyes in a mirror after a series of neck flexion exercises. Other methods of NHP registration include instructing subjects to look at a small light (Cleall, 1965), the use of a fluid level device (Showfety *et al.*, 1983), an operator-estimated 'natural head orientation' (Lundström *et al.*, 1995), and the use of an inclinometer (Preston *et al.*, 1997). NHP can be recorded radiographically (Bjern, 1957; Moorrees and Kean, 1958) or photographically, which is preferred to allow the most freedom in producing a natural position (Lundström and Lundström, 1989).

NHP as a craniofacial reference system has been advocated mainly because of its good intraindividual reproducibility to a true vertical plumb line on two or more occasions. Short-term reproducibility has been confirmed by a mean square error of 2.05 degrees (Moorrees and Kean, 1958) while long-term reproducibility has been associated with a mean square error of 1.9 degrees (Cooke, 1990) at 5 years and 2.23 degrees at 15 years (Peng and Cooke, 1999). Additional features that validate the use of NHP in cephalometric analysis include its representation of a true

Table 1 Literature summary illustrating the average orientation and variability of sella–naison (SN) and Frankfurt Horizontal (FH) to true vertical (VER).

Author (year)	*n*	SN/VER (°)		FH/VER (°)	
		Mean	SD	Mean	SD
Downs (1952)	100			88.1	5
Downs (1956)	100			87.7	5
Bjern (1957)	35	94.3	3.99	87.2	4.6
Moorrees and Kean (1958)	61	94.7	3.9	87.79	4.02
Solow and Tallgren (1971)	120	92.6	4.2		
Siersbæk-Nielsen and Solow (1982)	30	98.42	5.1		
Cole (1988)	20	93.6	7.6	89.9	9.1
Tallgren and Solow (1987)	81	99.6	3.58		
Sandham (1988)	12	93	5		
Cooke and Wei (1988b)	120	96.8	5.6		
Lundström *et al.* (1992)	27	93.8	5.6	84.9	5.3
Huggare (1993)	28	98.6	5.2		
Lundström and Lundström (1995)	39	92.6	5.4	88.4	5.2
Solow and Sonnesen (1998)	96	96.3	6.1		
Leitão and Nanda (2000)	284	98.19	4.45	89.27	5.02

life appearance (Cooke and Wei, 1988a; Lundström and Lundström, 1992) and its ease of registration. However, the use of NHP is not widespread, perhaps due to practical constraints such as equipment and staff training. Additionally, records taken in NHP are not always available. Thus, it seems appropriate that other reference planes apart from SN and FH might be used, if they are less variable between individuals and orientated closer to HOR.

Other intracranial planes tested for validity by evaluating interindividual variability and average orientation include the palatal, functional occlusal, mandibular, *y*-axis, nasion–pogonion, point A–point B (Cooke and Wei, 1988b), basion–nasion (Lundström and Lundström, 1992), and pterygomaxillary vertical (Leitão and Nanda, 2000). All these craniofacial planes have been shown to display variability as large as FH and SN. Also their average orientation is not close to HOR, with the exception of the palatal plane. NHP has a clinically acceptable reproducibility and, thus, it has been concluded that true vertical or horizontal planes derived from a NHP registration represent a more valid craniofacial reference system (Lundström and Lundström, 1992).

No studies to date have investigated the interindividual variability and average orientation of the Krogman–Walker (KW) line, neutral horizontal axis (NHA), foramen magnum line (FML), or posterior maxillary (PM) plane to true horizontal. The KW line (Rothstein and Yoon-Tarlie, 2000), which passes from occipitale to maxillon, encompasses the oropharynx and, therefore, may possess a biological consistency to maintain the airway. Additionally, the NHA, which essentially passes along the optic canal, may have a constant relationship to HOR by means of vision and balance. Therefore, the aim of the present study was to evaluate the variability of these craniofacial reference planes, as well as several others, in relation to true horizontal. The hypothesis tested was that the KW line and palatal plane would show variability similar to FH and SN to HOR and that they would be orientated closer to true HOR.

Materials and methods

Ethical approval for the present investigation was obtained from the Human Research and Ethics Committee, University of Adelaide (approval number H-136-2005) and written consent obtained for all subjects.

Sample

Fifty-seven subjects (38 female, 19 male), aged 12–18 years, were selected consecutively from pre-treatment patients attending the Orthodontic Department, Adelaide Dental Hospital, Australia. The subjects were from a variety of ethnic backgrounds, representing the usual cross-section of patients treated, with an appropriate age, agreement to participate, and absence of major craniofacial dysmorphia being the selection criteria.

All subjects at the initial examination (T1) were photographically recorded in a standing mirror-guided NHP using a protocol based on the method of Solow and Tallgren (1971). This involved each subject performing a series of neck-bending exercises and, while looking into their eyes, walking into a position 1 metre away from a 20 × 100 mm wall-mounted mirror. A true vertical plumb line (VER) in front of each subject's profile defined the true vertical. Each subject was then instructed to keep their teeth lightly closed together, at which point a lateral head photograph was obtained with standardized photographic equipment as described by Lundström and Lundström (1992). The statistical power to detect a clinically significant change of 2 degrees for the 57 subjects was 0.82 ($P = 0.05$). At T2, an average of 2 months later (SD 1.1 months), a second photographic NHP registration was collected for 39 of these subjects.

A lateral radiograph was obtained for each subject at T1, traced, and digitized by the same observer (DPM). To produce a tracing orientated in NHP, the true vertical plumb line was transferred from the photograph to the tracing by electronic superimposition of the nose and forehead soft tissue profiles (Adobe Photoshop CS, Adobe Systems Inc., San Jose, California, USA) with allowance made for magnification distortion. The same tracing was later re-orientated to VER in the same way, using the second NHP registration at T2. A true horizontal plane (HOR) was constructed perpendicular to the vertical plumb line of each tracing. Using the Mona Lisa Craniofacial Planner software package (Tidbinbilla Pty Ltd, Canberra, Australia), a cephalometric analysis based on the work of Barbera (2005) was performed.

Table 2 Results of cephalometric analysis at initial examination ($N = 57$). Only positive coefficients of variation were determined.

	Mean	SD	Minimum	Maximum	CV (%)
Angular variables (°)					
HOR/FH	−4.82	4.63	−17.12	5.91	
HOR/SN	5.19	5.13	−9.88	14.86	98.9
HOR/StN	8.21	5.10	−7.05	18.02	62.9
HOR/NHA	−5.41	5.36	−23.13	6.04	
HOR/KW line	−3.05	4.67	−17.22	6.08	
HOR/P plane	−0.97	5.04	−13.37	9.77	
HOR/FML	3.39	6.45	−12.58	16.24	190.4
HOR/AtPt	11.16	7.67	−5.81	28.04	68.7
HOR/FOP	−11.18	5.27	−23.82	1.11	
HOR/Md plane	−24.54	6.84	−42.77	−10.49	
HOR/PM plane	83.79	4.68	69.44	93.22	5.6
FML/AtPt	7.83	5.92	−5.88	25.54	75.6
KW line/Md plane	−21.49	5.29	−35.82	−10.21	
NHA/PM plane	89.20	4.39	78.61	98.38	4.9
PM plane/PM vertical	−5.11	2.40	−10.73	0.16	
Linear variables (mm)					
Ba-cv2ap	4.58	1.70	1.58	9.13	37.2
Ba-KW line	4.87	2.27	0.10	11.38	46.6
Ba-Op	35.76	3.25	28.92	44.69	9.1
At-Pt	47.76	3.70	41.06	57.78	7.8

Data collection

Fifteen angular and four linear variables (Table 2) were measured at T1 to investigate the interindividual variability and average orientation of the craniofacial reference planes shown in Figure 1. All angles were defined as the minimum angular rotation from the first plane to the second, or alternatively, HOR to the reference plane. With the patient facing left, a clockwise rotation was assigned a positive value and an anticlockwise rotation a negative value. The exception to this was NHA/PM and HOR/PM planes which were defined as the magnitude of clockwise angular rotation from the first to the second plane.

NHP reproducibility was later determined by observing the difference in the variable HOR/SN at T1 and T2 for the 39 subjects followed up at T2. SN was chosen for its good reliability between T1 and T2 tracings.

Statistical analysis

The data at T1 were firstly visualized to confirm that they were normally distributed. With this condition satisfied, descriptive statistics including the mean values, SDs, ranges (minimum/maximum), and coefficients of variation were calculated for each variable. Comparisons of variance and mean values between the genders were made using *F*- and Student's *t*-tests, respectively. No significant gender differences were found and the data were pooled for the 57 subjects for further interpretation. Pearson's correlation coefficients were calculated to quantify the strength of association between pairs of angular variables.

NHP reproducibility over a 2 month period was quantified by double determinations of the variable HOR/SN at T1 and T2 ($N = 39$). The mean difference was calculated and tested for significance using a paired *t*-test. The SD of the difference and mean square error (Dahlberg, 1940; Houston, 1983), $S(i)$, were also determined. Significance for all statistical tests was set at $P < 0.05$.

Method error

To determine the error in landmark location, tracing orientation, and measurement, a method error study was performed for 20 randomly chosen subjects through double determinations. At least 1 month after the initial T1 tracing, each lateral cephalogram was retraced by the same observer (DPM), orientated in NHP, digitized, and measured. Systematic errors were assessed using a paired *t*-test. Random errors were quantified using the mean square error, $S(i)$, and the coefficient of reliability (Houston, 1983).

Results

Of the 57 subjects photographically recorded in NHP at T1, 39 subjects were followed up for a second photographic NHP registration at T2. On average, the time interval between T1 and T2 was 2 months (SD 1.1 months). The lateral cephalogram was obtained at the same time as the T1 photograph for all subjects. The average age of the subjects at T1 was 15.4 years (SD 1.5 years).

The method error was examined as described previously and these results are presented in Table 3. Statistically significant systematic errors were found for variables HOR/KW line, HOR/P plane, HOR/FOP, FML/AtPt, Ba-Op, and At-Pt. The random errors ranged between 0.41 and 1.28

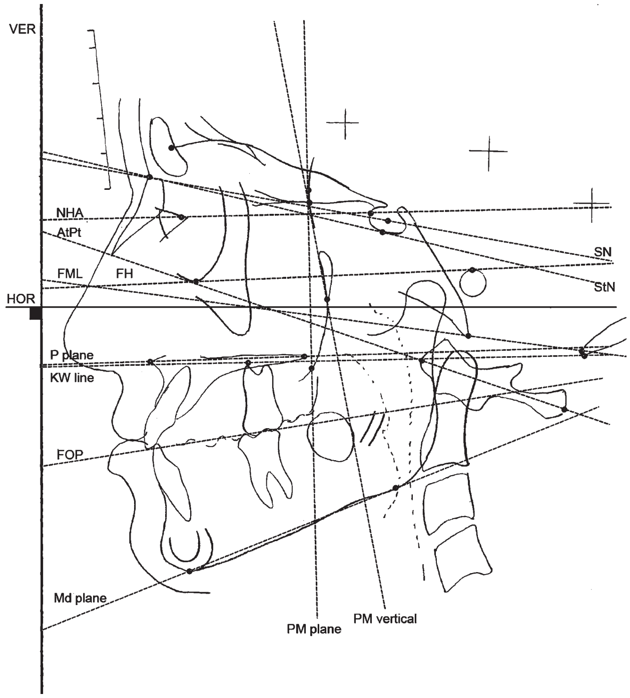

Figure 1 Craniofacial reference planes investigated. HOR, true horizontal constructed perpendicular to the vertical plumb line (VER); FH, Frankfort Horizontal; SN, sella–nasion; StN, sella tangent–nasion (Sassouni, 1955); NHA, neutral horizontal axis (McCarthy and Lieberman, 2001); KW line, Krogman–Walker line (Rothstein and Yoon-Tarlie, 2000); P plane, palatal plane; FML, foramen magnum line; AtPt, anterior tubercle to posterior tubercle of C1; FOP, functional occlusal plane; Md plane, mandibular plane, PM plane, posterior maxillary plane (Enlow and Azuma, 1975); PM vertical, pterygomaxillary vertical (Enlow *et al.*, 1969).

degrees. The coefficient of reliability ranged from 0.88 to 0.99 reflecting minimal error in landmark identification.

Reproducibility of NHP to true horizontal

The reproducibility of NHP over 2 months was evaluated by the difference in HOR/SN between T1 and T2. These results are presented in Table 4. The mean difference was close to zero over this period and was not statistically significant. The values of the SD of the difference and mean square error were 2.99 and 2.08 degrees, respectively. To visualize the reproducibility of NHP between T1 and T2, a box plot distribution is provided for comparison with the craniofacial reference planes related to HOR (Figure 2). The distribution of data for intraindividual NHP reproducibility was less than the interindividual variability of craniofacial reference planes related to HOR.

Variability and orientation of craniofacial reference planes to true horizontal

Descriptive statistics for the angular and linear variables are presented in Table 2. Interindividual variability of craniofacial reference planes to HOR was expressed in terms of SDs, ranges, and coefficients of variation. Distributions of data were also displayed in the form of box plots. Variability of the 11 craniofacial reference planes compared with HOR was generally high compared with the reproducibility of NHP. SDs for these planes ranged from 4.63 to 7.67 degrees. The angular variables with the lowest variability were HOR/FH and HOR/KW line, with SDs of 4.63 and 4.67 degrees, respectively. However, another six variables (HOR/SN, HOR/StN, HOR/NHA, HOR/P plane, HOR/FOP, and HOR/PM plane) exhibited SDs within 1 degree of these. The value of observed ranges for angular variables related to HOR were also generally large. The lowest value was 22 degrees for HOR/P plane while HOR/AtPt displayed the highest range of 34 degrees. The value of the coefficients of variation was lowest for HOR/PM plane being 5.6 per cent and highest for HOR/FML, 190.4 per cent. Visual inspection of the box plot distribution of data for the variables compared with HOR displayed the smallest distribution for HOR/FH and HOR/KW line with the largest distribution for HOR/AtPt and HOR/Md plane (Figure 2).

Average orientation of the craniofacial reference planes to HOR was expressed in terms of the mean values (Table 2). The angular variables with the closest average orientation to HOR were the HOR/P plane and HOR/KW line, with mean values of −0.97 and −3.05 degrees, respectively. HOR/Md plane displayed the largest average orientation from HOR, with a mean value of −24.54 degrees while HOR/PM plane was closest to VER, with a mean value of 83.79 degrees.

Pearson correlation coefficients, quantifying the strength of association between pairs of angular and linear variables, are presented in Table 5. For both males and females, six were highly correlated variables ($r > 0.80$). These were HOR/FH and HOR/NHA, HOR/FH and HOR/KW line, HOR/SN and HOR/StN, HOR/SN and HOR/NHA, HOR/StN and HOR/NHA, and HOR/NHA and HOR/KW line.

Discussion

Method error

Random errors were generally small, indicating good reliability for the reference planes investigated (Table 3). Only four angular variables displayed systematic errors, which is suggestive of a change in observer practice between determinations. This may have been a consequence of the observer's relative inexperience when initially identifying the landmarks at T1 (Houston, 1983). However, the SD of the difference between determinations was 1.6 degrees at most. Therefore, it could be assumed that this error made less contribution to the interindividual variability of reference planes to HOR than the intraindividual reproducibility of NHP between T1 and T2, SD 2.99 degrees (Table 4).

Table 3 Method error results.

	N	Systematic error				Random error	
		Mean difference	SD difference	*t*-test	*P*	*S*(*i*)	Reliability
Angular variables (°)							
HOR/FH	20	−0.04	0.90	0.18	0.86	0.62	0.98
HOR/SN	20	0.11	0.88	0.55	0.59	0.61	0.99
HOR/StN	20	−0.18	0.82	1.00	0.33	0.58	0.99
HOR/NHA	20	0.31	1.43	0.97	0.34	1.01	0.96
HOR/KW line	20	−0.44	0.57	3.23*	0.00*	0.50	0.99
HOR/P plane	20	−0.80	1.21	2.80*	0.01*	1.01	0.96
HOR/FML	20	−0.57	1.26	1.96	0.06	0.96	0.98
HOR/AtPt	20	−0.06	0.70	0.36	0.72	0.48	0.99
HOR/FOP	20	0.82	1.65	2.14*	0.04*	1.28	0.94
HOR/Md plane	20	−0.16	0.69	1.04	0.30	0.49	0.99
HOR/PM plane	20	−0.47	1.01	2.02	0.05	0.77	0.97
FML/AtPt	20	0.35	1.59	2.38*	0.02*	1.12	0.96
KW line/Md plane	20	0.28	0.61	1.15	0.26	0.47	0.99
NHA/PM plane	20	−0.78	1.12	0.96	0.34	0.95	0.95
PM plane/PM vertical	20	−0.14	1.04	1.96	0.06	0.72	0.91
Linear variables (mm)							
Ba-cv2ap	20	0.30	0.81	1.59	0.12	0.60	0.88*
Ba-KW line	20	0.01	0.81	0.08	0.94	0.56	0.94
Ba-Op	20	−0.59	1.19	2.15*	0.04*	0.92	0.92
At-Pt	20	0.28	0.52	2.30*	0.03*	0.41	0.99

*Indicates significant values of $P < 0.05$ and reliability values <0.90.

Table 4 Reproducibility of natural head position (NHP) [measured by the difference in the angular variable true horizontal (HOR) to sella–nasion (SN) at the initial examination and follow-up].

Angular variables (°)	*N*	Mean difference	SD difference	*t*-test	*P*	*S*(*i*)
HOR/SN	39	−0.0004	2.99	0.0008	0.9993	2.08

Reproducibility of NHP

By observing the difference in HOR/SN at T1 and T2 (Table 4), NHP reproducibility over a 2 month period was found to be associated with a mean square error of 2.08 degrees. A period of 2 months was felt to be sufficiently long to minimize any patient memory bias, while short enough to control any soft tissue profile growth effects. SN displayed acceptable method error results (Table 3), which provided a reliable reference to determine NHP reproducibility to HOR. This result is comparable with previous investigations of NHP reproducibility that report mean square error values ranging from 1.1 to 3.2 degrees (Moorrees and Kean, 1958; Solow and Tallgren, 1971; McWilliam and Rausen, 1982; Siersbæk-Nielsen and Solow, 1982; Cole, 1988; Cooke and Wei, 1988b; Sandham, 1988; Cooke, 1990; Lundström and Lundström, 1992; Huggare, 1993; Peng and Cooke, 1999; Bister *et al.*, 2002; Usumez and Orhan, 2003).

Given the observed SD for NHP reproducibility of 2.99 degrees, two-thirds of the sample reproduced NHP within ±3 degrees between T1 and T2 and the remaining one-third within ±6 degrees. Therefore, it is evident that one of the main weaknesses in the use of NHP is its variable intraindividual reproducibility over time. For the third of subjects whose NHP registration differed by more than 3 degrees between T1 and T2, the use of a true vertical or horizontal reference plane for cephalometric analysis may be limited. Additionally, with such variation in NHP registration, it may be difficult to establish whether it is head position or anatomic variation that is the primary contributor to variability of reference planes to HOR. For the single outlier in Figure 2, it may have been head position that influenced the orientation of planes more. For this reason, a corrected head position has been advocated where NHP is deemed to be 'unnatural' (Moorrees and Kean, 1958).

NHP reproducibility is commonly reported as a mean square error or Dahlberg value. However, Bister *et al.* (2002) suggested that this formula has a tendency to camouflage the true variability of the results. Therefore, they advocated the use of the reproducibility coefficient and its graphical representation for NHP reproducibility assessment. Figure 2 is a box plot graphical distribution of data for the difference in HOR/SN at the two NHP registrations. Interestingly, the box plot for NHP is much smaller than those for the craniofacial reference planes when related to HOR. It is clear that the intraindividual reproducibility of NHP is less than the interindividual

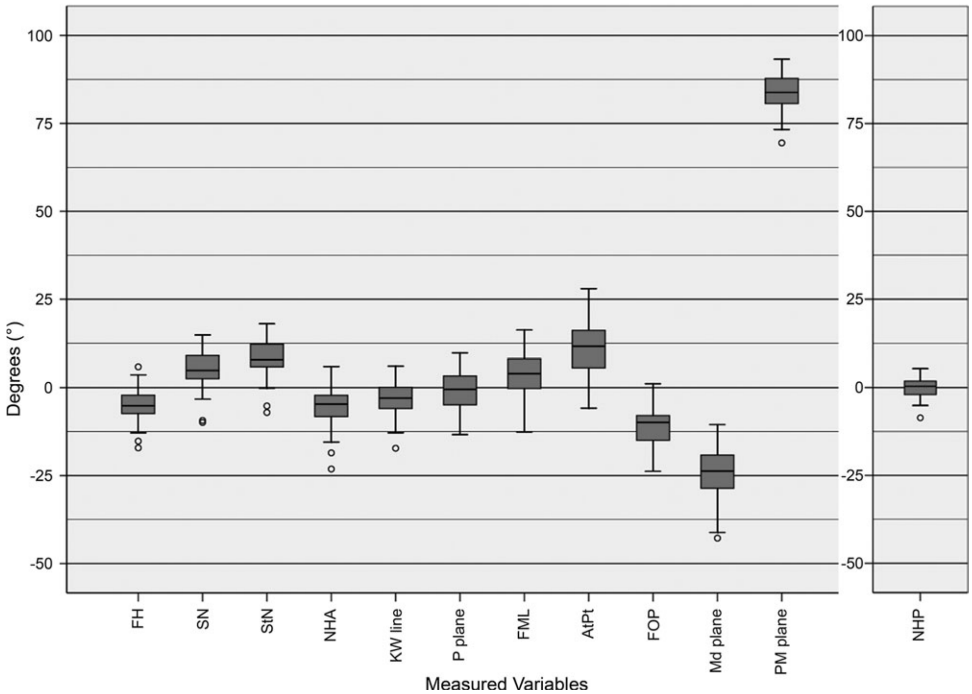

Figure 2 Box plots illustrating the variability (°) of craniofacial reference planes to HOR at the initial examination. For comparison, NHP represents the variability (°) of NHP to HOR between the initial examination and follow-up. Note how the upper and lower margins of the NHP box, representing the 25th and 75th per cent quartiles, illustrate a lower distribution than the other craniofacial planes.

variation in the orientation of the craniofacial reference planes to HOR. This validates the use of a true vertical or horizontal reference plane established from NHP registration in preference to other planes.

Variability and average orientation of craniofacial reference planes

It was found that the interindividual variability of the craniofacial reference planes was larger than the intraindividual reproducibility of NHP, with SDs for these planes ranging from 4.63 to 7.67 degrees. These findings were expected given the overall variation in craniofacial morphology in an unbiased sample.

The results of the present investigation, shown in Table 2, indicate that eight craniofacial reference planes related to HOR were associated with SDs within 1 degree of each other. This suggests that no particular plane had a lower variability than the others. Confirming this are the box plot distributions in Figure 2, illustrating a similar distribution of data for FH, SN, StN, NHA, KW line, palatel plane, FOP, and PM plane. Additionally, the estimated magnitude of interindividual variability of these planes was similar to previously published data (Table 1).

FH and the KW line showed the lowest variability to HOR with SDs of 4.63 and 4.67 degrees, respectively. This result for FH is consistent with previous investigations where a SD close to 5 degrees was found for VER/FH (Table 1). There are few comparative data illustrating the variability of the KW line to HOR/VER. Visually, its orientation lies between that of SN and FH (Figure 1) and on average it relates more closely to HOR (−3.05 degrees) compared with SN and FH (Table 2). In a similar investigation of the variability of craniofacial reference planes, the HOR/KW line displayed comparable results, with a SD of 5.2 degrees, and a close average orientation to HOR of −0.2 degrees (Barbera, 2005). On this basis, it would seem that both FH and the KW line show similar interindividual variability (Figure 2), but the KW line may represent a more valid craniofacial reference plane due on average, to its closer orientation to HOR.

Of all the craniofacial reference planes related to HOR, the palatal plane displayed the closest average orientation of −0.97 degrees. With only slightly more variability to HOR (SD 5.04) than the KW line, this too may provide a useful plane for cephalometric analysis. This is in agreement with previous investigations that found the HOR/P plane to be associated with a mean value of −0.5 to −5.45 and SD of 4.38 to 5.88 degrees (Solow and Tallgren, 1971; Cooke and Wei, 1988b; Solow and Sonnesen, 1998; Leitão and Nanda, 2000; Barbera, 2005).

SN showed a similar interindividual variability to HOR (SD 5.13) as FH and the KW line. Interestingly, Lundström and Lundström (1995), who also found almost equal

Table 5 Pearson correlation coefficients for angular and linear variables (males upper right, females lower left).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Angular variables																			
1. HOR/FH		0.78	0.76	**0.86**	**0.91**	0.63	0.44	0.32	0.46	0.49	0.41	−0.20	0.14	−0.37	0.11				
2. HOR/SN	**0.85**		**1.00**	**0.90**	0.74	0.64	0.47	0.12	0.44	0.70	0.39	−0.39	0.35	−0.42	0.21				
3. HOR/StN	**0.85**	**1.00**		**0.89**	0.72	0.64	0.46	0.10	0.44	0.68	0.39	−0.41	0.34	−0.41	0.23				
4. HOR/NHA	**0.84**	**0.96**	**0.95**		**0.83**	0.57	0.62	0.32	0.47	0.76	0.38	−0.25	0.37	−0.52	0.08				
5. HOR/KW line	**0.88**	**0.81**	**0.81**	**0.80**		0.67	0.71	0.52	0.33	0.70	0.50	−0.05	0.14	−0.25	0.05				
6. HOR/P plane	0.75	**0.80**	0.79	0.75	0.66		0.44	0.32	0.46	0.49	0.66	−0.03	0.12	0.11	0.15				
7. HOR/FML	0.74	0.67	0.67	0.66	0.87	0.56		0.77	0.15	0.38	0.18	−0.01	−0.07	−0.37	−0.30				
8. HOR/AtPt	0.38	0.44	0.45	0.43	0.42	0.47	0.59		0.03	0.26	0.06	0.63	−0.07	−0.22	−0.31				
9. HOR/FOP	**0.81**	0.75	0.73	**0.80**	0.74	0.73	0.67	0.50		0.65	0.66	−0.14	0.63	0.20	−0.34				
10. HOR/Md plane	0.68	0.63	0.61	0.71	0.61	0.58	0.60	0.56	**0.86**		0.56	−0.05	**0.81**	−0.14	−0.17				
11. HOR/PM plane	**0.84**	0.78	0.78	0.74	0.77	0.69	0.63	0.35	0.68	0.56		−0.12	0.36	0.59	0.03				
12. FML/AtPt	−0.31	−0.16	−0.16	−0.17	−0.41	−0.02	−0.33	0.56	−0.09	0.06	−0.23		−0.02	0.10	−0.12				
13. KW line/Md plane	0.07	0.07	0.05	0.18	−0.13	0.14	−0.02	0.33	0.42	0.71	0.02	0.43		0.01	−0.27				
14. NHA/PM plane	−0.24	−0.49	−0.48	−0.60	−0.26	−0.29	−0.24	−0.22	−0.38	−0.39	0.10	−0.03	−0.25		−0.04				
15. PM plane/PM vertical	0.21	0.10	0.12	0.04	0.10	0.13	0.04	−0.25	0.07	−0.04	0.26	−0.32	−0.14	0.25					
Linear variables																16	17	18	19
16. Ba-cv2ap																	−0.24	0.52	0.09
17. Ba-KW line																−0.30		−0.02	0.08
18. Ba-Op																0.46	0.03		0.43
19. At-Pt																−0.01	0.04	0.29	

Values of correlation >0.80 in bold.

variability in SN and FH, suggested that due to more vertical errors associated with locating porion and orbitale (to construct FH), the true interindividual variation of HOR/FH could be less than that of HOR/SN, where SN is easier to locate. From this, it was suggested that perhaps FH was a biologically more suitable reference plane than SN. However, the method error results in Table 3 show remarkably similar errors for variables HOR/FH and HOR/SN, which suggests that the ability to locate relevant landmarks for both planes was similar in the present study.

Associations between planes

Common or closely related landmarks appear to explain the majority of highly correlated ($r > 0.80$) planes. It is not surprising that the correlation coefficient for HOR/SN to HOR/StN was 1.00 for males and females. Both variables share a common landmark at nasion, while the posterior construction points at sella and sella tangent are anatomically highly interdependent given their relationship with the pituitary fossa.

However, there were some instances where this was not the case. HOR/FH and HOR/KW line showed correlation coefficients of 0.91 and 0.88 in males and females, respectively. Despite these high correlations, the construction points for FH and the KW line are at quite different anatomical locations within the maxilla anteriorly and in different bones posteriorly. This may suggest that there is anatomic interdependence or a consistent spatial relationship between these planes which might be driven by the morphology of the maxilla.

Furthermore, the variables HOR/NHA and HOR/KW line share no common anatomical landmarks, yet produced correlations of 0.83 and 0.80. This again suggests some form of morphological consistency, or alternatively, a spurious correlation because of the gender subpopulations being limited in size (males 19, females 38). However, with regard to head balance, NHA, representing visual input (Enlow *et al.*, 1969; McCarthy and Lieberman, 2001), and the KW line reflecting maxillary orientation to the basi-occiput, may be expected to show an association due to the need for functional coordination of vision, respiration, and mastication. Perhaps a constructed plane between NHA or the KW line and SN may represent a more valid craniofacial reference system due to such associations and their biological representation. The potential use of a combination of planes for reference plane construction is subject to future investigations.

The values of most correlation coefficients between pairs of variables were generally low. Leitão and Nanda (2000) highlighted that this explains why the inclination of the upper incisors measured with respect to two poorly correlated planes can give contradictory results. Therefore, with the commonly used craniofacial reference planes tending to be highly variable and poorly related, it is suggested that cephalometric analysis should be performed using more than one reference plane.

Conclusions

1. The investigated craniofacial reference planes displayed larger interindividual variability than intraindividual NHP reproducibility when both were related to true horizontal. Thus, it was confirmed that a true vertical or horizontal plane from a NHP registration represents a more valid craniofacial reference system.
2. When NHP is not used, the KW line and palatal plane both offer advantages as craniofacial reference planes compared with SN or FH because of their closer orientation to HOR and similar variability. Therefore, the hypothesis is retained.
3. NHA, FH, and KW line compared with HOR are highly correlated, reflecting common biological or functional mechanisms that are the subject of ongoing investigations.

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