NATURAL HEAD POSITION: A PHOTOGRAPHIC METHOD AND AN EVALUATION OF CRANIAL REFERENCE PLANES IN CEPHALOMETRIC ANALYSIS

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Clinical Dentistry (Orthodontics)

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3. Signed Statement

This report contains no new material that has been accepted for the award of any other degree or diploma in any other university. To the best of my belief, it contains no material previously published except where due reference is made in the text.

I give consent for this copy of my thesis, when deposited in the University library, to be made available for loan and photocopying.

David P. Madsen
25th October, 2007

4. Summary

Commonly used craniofacial reference planes such as Frankfort Horizontal (FH) and sella nasion (SN) have shortcomings including their variable inter-individual 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 before: Krogman-Walker line (KW line), neutral horizontal axis, foramen magnum line and posterior maxillary plane. A sample of 57 (38 female, 19 males) consecutive, pre-treatment orthodontic subjects aged 12 to 18 were photographically recorded in a standing mirror guided natural head position (NHP). Cephalograms taken at the same time were traced, oriented to a plumb line (true vertical) transferred from the photograph, and measured for statistical analysis. 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 lowest variability to HOR were FH and KW line with standard deviations of 4.6° and 4.7°, respectively. These, however, showed about double the variation in NHP reproducibility (Dahlberg 2.1°). The KW line and palatal plane were also oriented closest to HOR on average. Therefore, 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.

5. Literature Review

5.1 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 intra-individual reproducibility, low inter-individual variability, and average orientation close to true horizontal (HOR) or vertical (VER).

A commonly used craniofacial reference plane is sella-nasion, SN [1]. While this plane is reliable and, by representing the anterior cranial base, is biologically meaningful, it has been illustrated to have large inter-individual standard deviations when related to VER (Table 1). Therefore, due to this high inter-individual variability and its 2° to 9° 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 [2]. However, others have shown that FH not only displays large variability to VER (standard deviation), but is oriented on average 1° to 5° from HOR (Table 1). Another shortcoming of FH is the suggestion of its inferior reliability compared with that of SN [3] 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 1950's [2, 4, 5]. Broca [6] defined this head position as "when man is standing and his visual axis is horizontal, he is in the natural position". A typical method of registering natural head position is based on Solow and Tallgren's [7] work in which subjects are asked to stand in "orthoposition" [8] 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 [9], the use of a fluid level device [10], an operator estimated "natural head orientation" [3] and the use of an inclinometer [11].

NHP as a craniofacial reference system has been advocated mainly because of its good intra-individual reproducibility to a true vertical plumb line on two or more occasions. Short term reproducibility has been confirmed by a Dahlberg value of 2.05° [2] while long term reproducibility has been associated with a Dahlberg value of 1.9° [12] at 5 years and 2.23° at 15 years [13]. Additional features that validate the use of NHP in cephalometric analysis include its representation of a true life appearance [14, 15], 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 oriented closer to HOR.

Other intracranial planes tested for validity by evaluating inter-individual variability and average orientation include the palatal, functional occlusal, mandibular, Y axis, nasion-pogonion, A point-B point [16], basion-nasion [15], and pterygomaxillary vertical [17]. All of 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 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.

No studies to date have investigated the inter-individual variability and average orientation of Krogman Walker line (KW line), neutral horizontal axis (NHA), foramen magnum line (FML) or posterior maxillary plane (PM plane) to true horizontal. KW line [18], which passes from occipitale to maxillon, encompasses the oropharynx and, therefore, may possess a biological consistency to maintain the airway. Additionally 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 and average orientation of these craniofacial reference planes, as well as several others, in relation to true horizontal. The hypothesis tested was that KW line and palatal plane would**

show variability similar to FH and SN to HOR and that they would be orientated closer to true horizontal, HOR (Section 6).

5.2 Craniofacial Reference Planes

Lateral radiography of the head held in a cephalostat has provided the opportunity to perform two types of cephalometric analysis. These are firstly, an inter-individual comparison of craniofacial morphology and, secondly, a longitudinal intra-individual comparison. Both forms of analysis are based upon a number of craniofacial reference planes, from which aspects of craniofacial morphology are measured. Therefore, it is evident that these reference planes and their properties are critical to the clinical interpretation of such analyses.

5.2.1 Properties of An Ideal Craniofacial Reference Plane/System

An ideal craniofacial reference plane or system should have the following features: good reliability (low method error), good intra-individual reproducibility, low inter-individual variability, and average orientation close to true horizontal (HOR) or vertical (VER).

Reliability refers to the ability of the operator to identify and construct such reference planes with little systematic or random error on two or more successive occasions. To minimise such error, cephalometric landmarks should be superimposed on as few structures as possible and be sufficient in contrast from their neighbouring radiographic structures. The definition of such landmarks should be clear and reference plane construction from these should not be complicated.

Intra-individual reproducibility refers to how the reference plane or system changes over time. Factors influencing the reproducibility of landmarks may be growth, while muscular control of the head and neck may influence reference systems based on head position.

Inter-individual variability is the variability of a selected reference plane between two or more individuals when related to HOR or VER. This is largely influenced by inter-

individual variation in craniofacial morphology and, to a lesser extent, the reproducibility and reliability of obtaining a HOR or VER reference plane.
Average orientation of a reference plane is the average inclination of a reference plane to HOR or VER, in a population group.

A number of reference planes or systems have been suggested. However no reference plane or system is ideal. Krogman [19] classifies the craniofacial reference planes into four broad categories.

a) Resting horizontal planes
b) Planes using various craniometric points
c) Planes centering upon the external auditory meatus
d) Radiographic cephalometric planes

5.2.2 Resting Horizontal Planes

These planes utilise the morphology of skulls when placed to rest on a horizontal surface. Due to landmark variability, these planes are inherently variable and yet serve as a means of two skull comparison without applying the concept of average types.

1. **Blumenbach's Plane** – The skull without its mandible is placed on a horizontal surface and the points of contact to this surface are noted. First described in 1804 by Blumenbach [20, 21], the father of physical anthropology, this plane passes through the points of contact at the maxillary teeth anteriorly and mastoid processes posteriorly (Figure 1).
2. **Von Baer's Plane** – Recognising that some skulls have missing teeth or damaged cranial bases, this plane is roughly parallel to Blumenbach's plane and is formed by drawing a tangent at the superior most concavity of the zygomatic arch [22] (Figure 1).

5.2.3 Planes Using Various Craniometric Points

These planes use readily identifiable landmarks on a dry skull in an attempt to eliminate the problems of variability seen in the above group. The below planes are outlined in Figure 2.

1. **Broca's Plane** – Extending from the alveolar point (the junction of upper central incisors to alveolar process) to the most inferior point of the occipital condyle when the skull is resting on a horizontal surface. This was an attempt to improve Blumenbach's plane.
2. **His' Plane** – Passes from anterior nasal spine (ANS) to opisthion. This defines both ends of the plane well and is not affected by tooth loss. However, ANS is quite variable and can often be broken on a dry skull.
3. **Martin's Plane** – This extends from nasion to inion (the most elevated point on the external occipital protuberance). However inion can be variable in size, increases in size with age, and tends to be larger in males [19].
4. **Huxley's Plane** – Otherwise known as "Huxley's basicranial axis" passes from nasion to basion. Krogman [19] felt that this plane could not be improved upon if it weren't for the difficulty in finding basion on the radiograph.
5. **Hamy's Plane** – Extended from glabella to lambda. This line was designed to compare contour drawing of calvarial remains [19].
6. **Schwalbe's Plane** – Extends from glabella to inion. This line was designed to compare contour drawing of calvarial remains.
7. **Schmidt's Plane** – Extends from ophyron (the midsaggital intersection on the frontal bone of a transverse line connecting the closest approximation of the left and right linae temporales [19]) to inion. This line was designed to compare contour drawing of calvarial remains.

5.2.4 Planes Centering Upon the External Auditory Meatus

Quite a few of these planes have been used in serial growth superimposition and analysis. These planes are illustrated in Figure 3.

1. **Camper's Plane -** One of the first reference planes described was by Camper [23] in 1768. The Camper Plane was defined as passing through the external auricular canal and the nasal lateral wing. It is evident that this definition has a degree of variable interpretation, thus decreasing its accuracy and validity as a cranial reference plane. Additionally, being developed prior

to the discovery of radiographic imaging, this plane may not be readily identifiable on the lateral head radiograph.

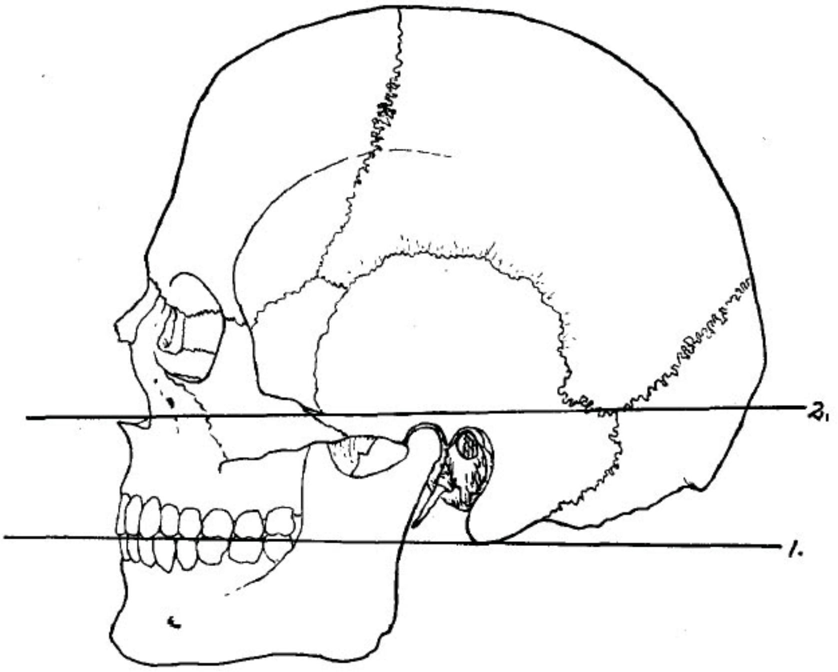


Figure 1. Resting horizontal planes 1. Blumenbach's Plane 2. Von Baer's Plane [19]

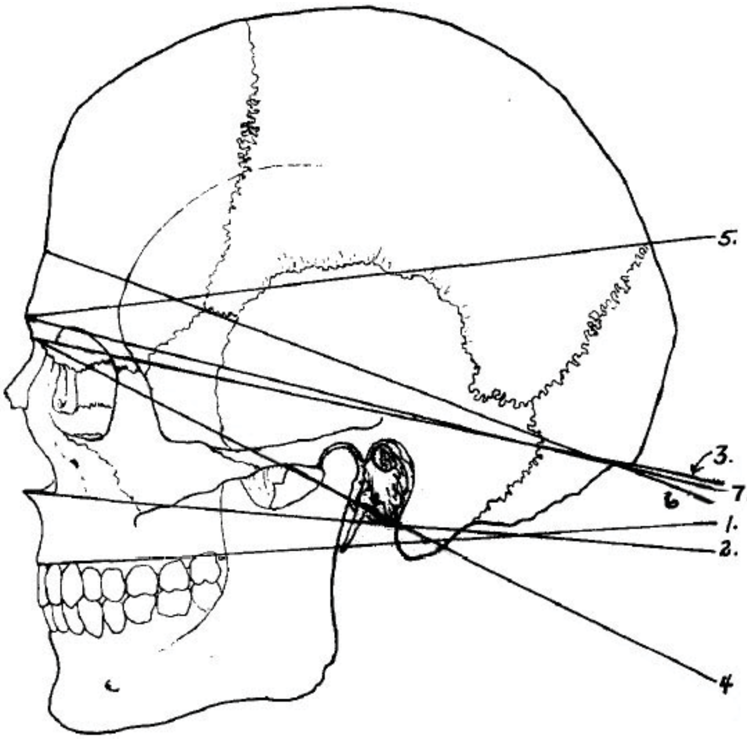


Figure 2. Planes using various cephalometric points. 1. Broca's Plane, 2. His' Plane, 3. Martin's Plane, 4. Huxley's Plane, 5. Hamy's Plane, 6. Schwalbe's Plane 7. Schmidt's Plane [19]

2. **Von Ihring's Plane** – This is the precursor to the well known Frankfort Horizontal. This extends from orbitale to the centre of the bony external auditory meatus [24].
3. **Pycraft's Plane** – Passes from nasion to the centre of the bony external auditory meatus. This plane is likely to have developed from Huxley's plane [19].
4. **Montague's Plane** – This eliminates the uncertainty involved when defining the centre of the bony external auditory meatus by using the posterior end point. This plane extends from nasion to porion (the most lateral point on the roof of the bony external auditory meatus).
5. **Frankfort Horizontal** - Frankfort Horizontal took a decade of development as anthropologists and craniologists attempted to develop a more suitable craniofacial reference plane.

   In 1872, Von Ihering [24] suggested a reference plane passing from the lowest point of the orbit (orbitale) through the midpoint of the *porus acousticus externus* as the most dorsal point.

   Subsequently in 1882, at the Craniometrical Conferences in Munich and Berlin, Von Ihering's line was modified. Porion was felt to be a more suitable dorsal landmark, creating the line from porion to orbitale which was labelled German Horizontal. It became known as Frankfort Horizontal after also being adopted at the Craniometrical Conference in Frankfurt am Main, 1884 [2].

   This plane was felt to produce the most acceptable approximation of true horizontal, yielding maximal differences in facial configuration between racial groups and supposedly the smallest variability within each group [25].
6. **Krogman "Nasion-Parallel"** – Which is essentially a plane passing through nasion parallel to a previously drawn Frankfort Horizontal [19].

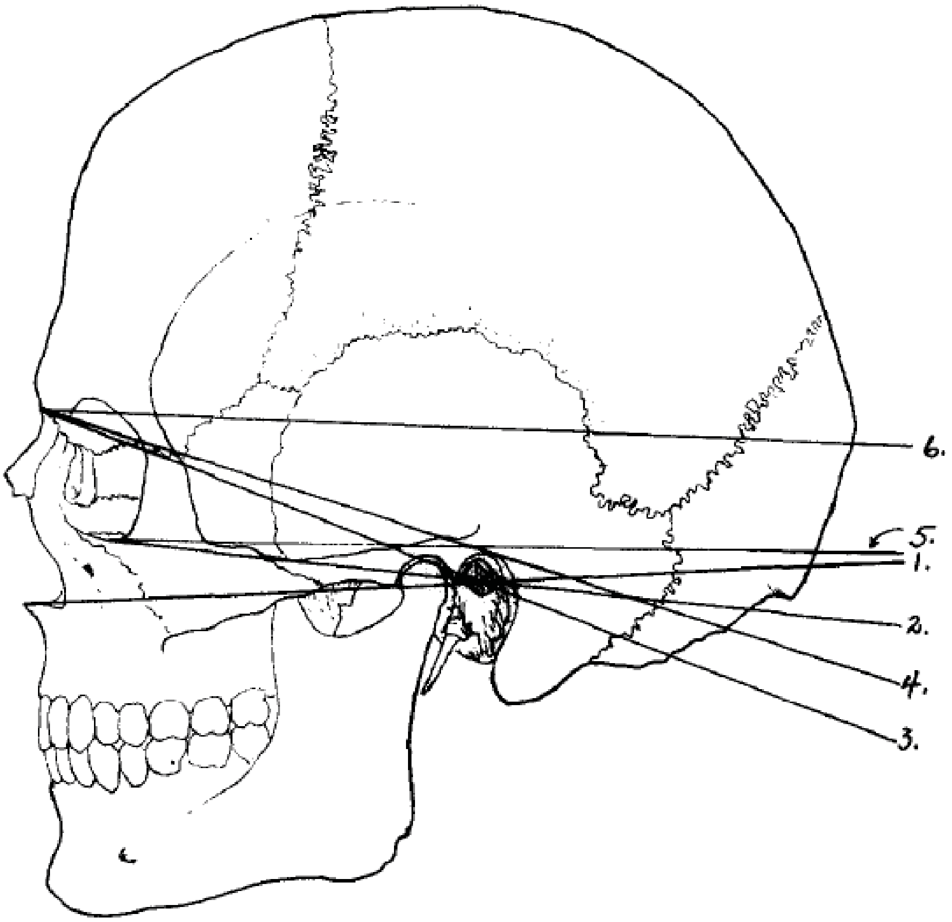


Figure 3. Planes centering upon external auditory meatus. 1. Camper's plane, 2. Von Ihering's plane, 3. Pycraft's plane, 4. Montegue's plane, 5. Frankfort Horizontal, 6. Krogman's "Nasion parallel" [19]

5.2.5 Radiographic Cephalometric Planes

These planes exclusively relate to those planes that can only be identified on a lateral head radiograph. These planes are illustrated in Figure 4.

1. **Broadbent's Plane** – Extends from nasion to sella. The rationale of using this plane relates to it representing the anterior cranial fossa and therefore neuro-orbital growth which reaches cessation after early childhood and thus is relatively stable [19]. In this way, subsequent facial growth must occur down and forward away from SN. However, it must be noted that any plane using nasion is subject to variability as nasion remodels and the underlying frontal sinus grows.
2. **Broadbent-Bolton Plane** – This passes from nasion to the Bolton point (which on a lateral head radiograph, is the uppermost point in the postcondylar fossa). This is quite similar in orientation to Huxley's plane.

3. **Margolis Plane** – This extends from nasion to the top of the spheno-occipital synchondrosis. Of course, the main weakness of this reference plane is the questionable reliability of its posterior point.
4. **Björk Plane** – Which passes from nasion to articulare. Because articulare is a superimpositional radiographic artefact of the ascending ramus intersecting with the contour of the temporal bone, it is prone to variability with altered patient head orientation and mandibular position.
5. **SN minus 7°**

   Frankfort Horizontal has been found to be canted approximately 7° from SN but with a degree of variation in the population. Therefore, SN minus 7° was developed by some authors [26, 27] in an attempt to create a craniofacial reference plane that was visually close to true horizontal, and independent of the variable nature of Frankfort Horizontal. Of course, this plane is really no different to SN with inherent problems of variability and change with growth.

5.2.6 Other Cephalometric Reference Planes

There are many other planes that have been developed for the purpose of providing a cephalometric reference plane. However, only an additional selected few will be outlined in this paper.

1. **PM Vertical (posterior nasomaxilla)** – First described by Enlow et al. [28] in 1969, this passes inferiorly from SE point (ethmoid registration point) along the posterior surface of the maxillary tuberosity through PTM (pterygomaxillary fissure, inferior). In Enlow's analysis [28], all vertical planes were made parallel to this key reference plane (Figure 5). PM vertical was claimed to be approximately perpendicular to the line of vision and to represent a reference line consistent with the anatomically neutral position of the head [29].

NOTE: This figure is included on page 21 of the print copy of the thesis held in the University of Adelaide Library.

Figure 4. Radiographic cephalometric planes. 1. Broadbent's Plane, 2. Margolis Plane, 3. Broadbent-Bolton Plane, 4. Björk Plane, 5. SN -7°[19]

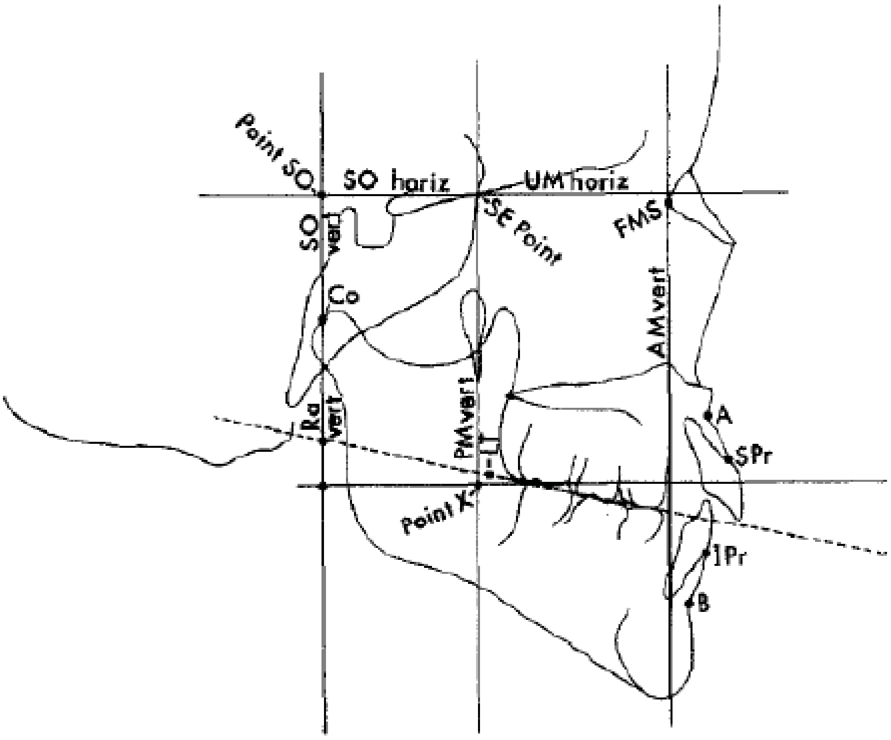


Figure 5. PM Vertical plane used in the Enlow Analysis[28]

2. **PM Plane** – This represents a later development of the PM vertical line. According to the definition by Enlow and Azuma [30] passes from PM point [31] (the average midline point of the anterior-most point on the lamina of each greater wing of the sphenoid) to Ptm (Pterygomaxillare) (Figure 6). Several studies argue that this plane remains at 90° to neutral horizontal axis [29, 31].

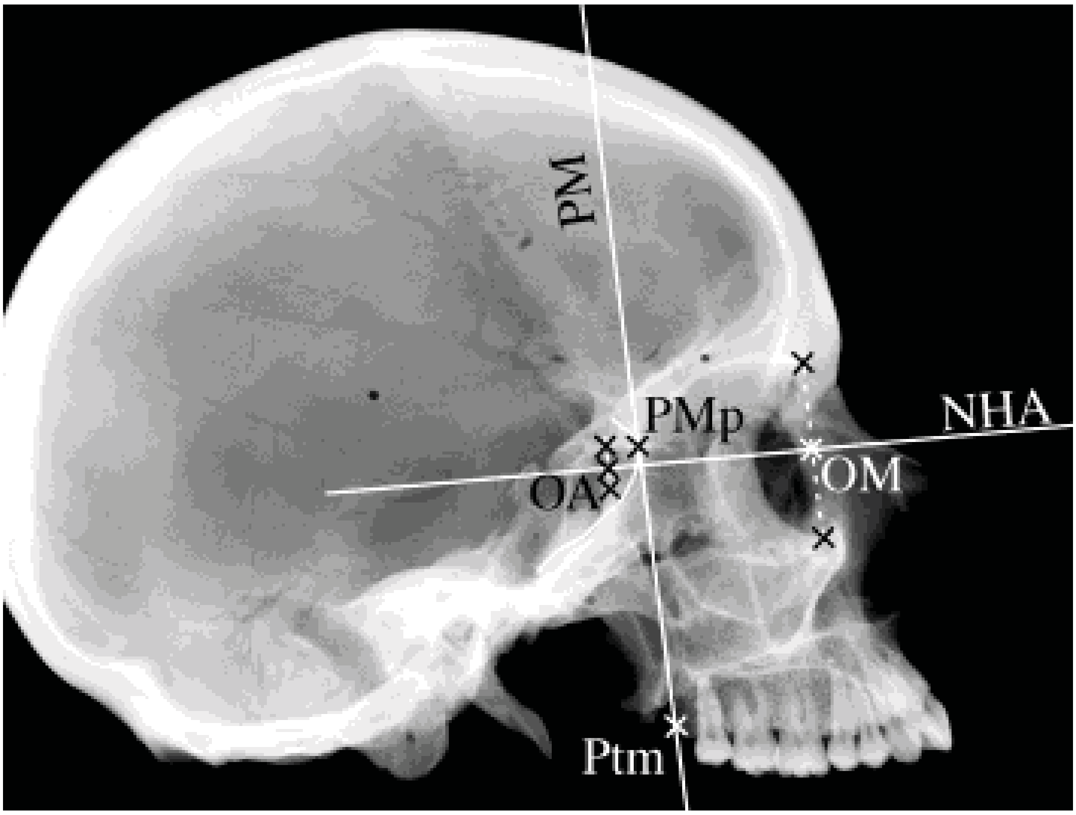


Figure 6. PM plane and Neutral Horizontal Axis [31]

3. **Neutral Horizontal Axis** – Is a line passing through the inferior border of the optic canal [31]. It is defined as passing through orbital margin point (OM – superoinferior midpoint between the superior and inferior orbital rims) and orbital axis point (OA – superoinferior midpoint between the superior orbital fissures and the inferior rims of the optic canals) [29, 31] (Figure 6).
4. **Krogman-Walker Line** – This is defined in Rothstein & Yoon-Tarlie [18] as the line passing through occipitale and maxillon (Figure 7).

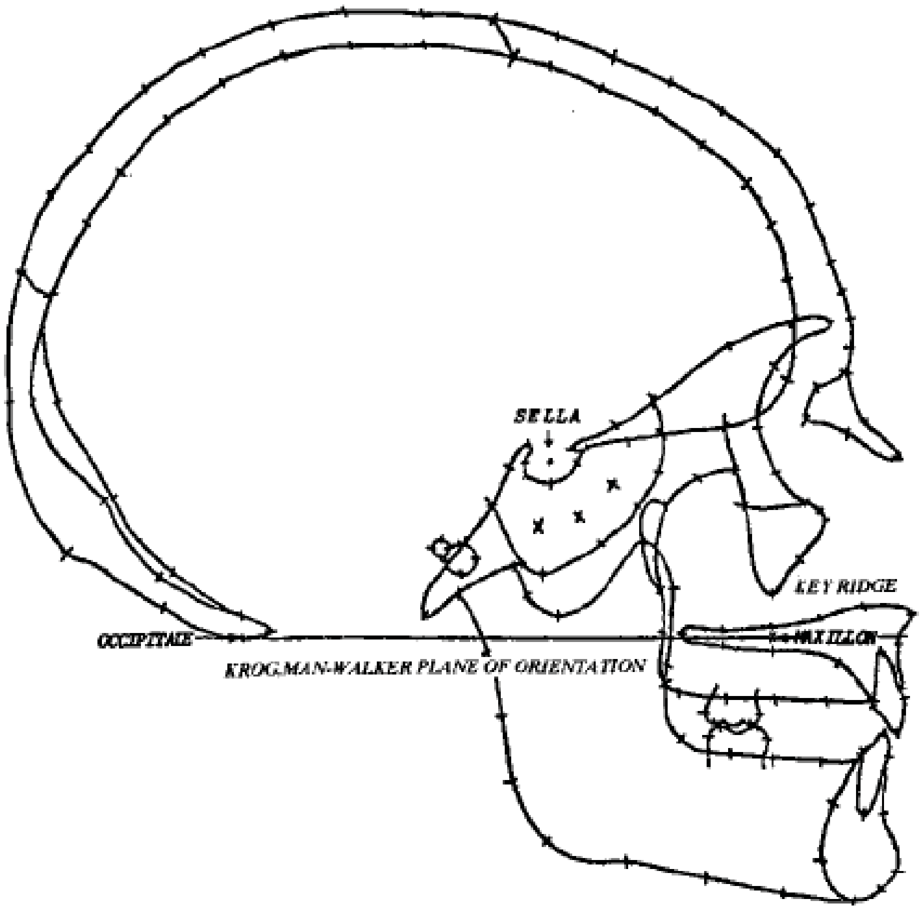


Figure 7. Krogman-Walker Plane [18]

Many of the above lines show an adequate degree of reliability in terms of landmark identification and low method error when tracing. Such lines are therefore useful for longitudinal comparisons of growth or treatment in *one individual*, such as in cephalometric superimposition. However, due to their inherent variability *between individuals*, such lines may be less useful for comparing an individual to others [2, 5, 32]. This has implications for the "cephalometric norms" that are used so often in orthodontics for cross-sectional cephalometric analysis. It is therefore evident that when performing a cross-sectional cephalometric analysis, comparing an individual's measurements to a sample of "normals" must take into account the variability of the reference planes used, i.e., variation of the chosen reference plane in the "normal" sample.

5.3 The Variation of Craniofacial Reference Planes

The variability of craniofacial reference planes refers to the inter-individual variation in inclination of a selected plane to HOR or VER. Statistically, the standard deviation of inclination is an indication of this. The following is an outline of those investigations that have measured the variability of a range of reference planes.

Björk [33] in 1950 published a paper on facial prognathism that highlighted the unreliability of intracranial reference lines. He selected two individuals to represent "maximum and minimum facial prognathism in adult male" relative to the line sella-nasion, but without reference to natural head position. Bjork presents two individuals who had almost identical profiles but illustrated great difference in inclination of their cranial base rather than differences in prognathism.

Downs [34] in 1952 is one of the first investigators to observe the inter-individual variability and average orientation of Frankfort Horizontal as a reference plane. In a study consisting of 100 subjects, Downs tested the notion that Frankfort Horizontal is level with the ground. A lateral profile photograph was taken of 100 consecutive patients while standing and looking into their own eyes in a mirror placed 5 feet away. By doing so, this was the first time the concept of natural head position and true horizontal was introduced into the orthodontic literature. Downs found the mean position of Frankfort Horizontal to be -0.9° deviated from true horizontal on average with a standard deviation of 5°. In other words, with the patient facing left, FH produced an average orientation that was 0.9° counter-clockwise from HOR. Downs made no mention of the error involved with determining Frankfort Horizontal from a lateral head photograph.

In 1956, Downs [5] tested this concept again and found similar results. Frankfort Horizontal was -1.3° deviated from true horizontal on average with a standard deviation of 5° (Figure 8). Mention was made of possible inaccuracies when recording a natural, free balanced head posture such as tenseness and excitement in the subject. Some judgement was required to determine this head position.

NOTE: This figure is included on page 25 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8. Variation of Frankfort Horizontal in lateral head photographs [5]

In 1957, Bjern [4] furthered Downs work by taking lateral head radiographs and photographs of 35 standing and sitting subjects in what was termed a “natural” position of the head. Frankfort Horizontal in this investigation was also found to deviate from true horizontal by an average of -1.8° with a standard deviation of 4.6°. This further strengthened the argument that Frankfort Horizontal illustrates significant variability across a population.

Additionally, it was shown that sella-nasion deviated from true horizontal by an average of 4.3° with a standard deviation of 3.99° (Figure 9).

NOTE: This figure is included on page 25 of the print copy of the thesis held in the University of Adelaide Library.

Figure 9. Means and standard deviations of SN and FH to true horizontal [4]

In fact, these early works of Downs and Bjern were the first of many papers in the orthodontic literature illustrating the variability of Frankfort Horizontal (FH) and sella-nasion (SN) to true horizontal or vertical. A brief summary of the literature is outlined below in Table 1.

Table 1. Literature summary illustrating the variance of SN and FH to true vertical (VER)

		SN/VER (°)		**FH/VER (°)**	
Author, Year	**n**	**Mean**	**SD**	**Mean**	**SD**
Downs, 1952 [34]	100			88.1	5
Downs, 1956 [5]	100			87.7	5
Bjern, 1957 [4]	35	94.3	3.99	87.2	4.6
Moorrees & Kean, 1958 [2]	61	94.7	3.9	87.79	4.02
Solow & Tallgren, 1971 [7]	120	92.6	4.2		
Siersbæk-Nielsen & Solow, 1982 [35]	30	98.42	5.1		
Cole, 1988 [36]	20	93.6	7.6	89.9	9.1
Tallgren & Solow, 1987 [37]	81	99.6	3.58		
Sandham, 1988 [38]	12	93	5		
Cooke & Wei, 1988 [39]	120	96.8	5.6		
Lundström & Lundström, 1992 [32]	27	93.8	5.6	84.9	5.3
Huggare, 1993 [40]	28	98.6	5.2		
Lundström & Lundström, 1995 [41]	39	92.6	5.4	88.4	5.2
Solow & Sonneson, 1998 [42]	96	96.3	6.1		
Leitão & Nanda, 2000 [17]	284	98.19	4.45	89.27	5.02

The above table illustrates the inter-individual variability of SN to true vertical with standard deviations ranging from 3.6° to 7.6°. Likewise a significant range of variability of FH to true vertical is evident with standard deviations ranging from 4.02° to 9.1°. One must recognise that these results are only valid if the intra-individual reproducibility of head position to VER is less than the inter-individual variation of craniofacial reference planes measured.

Other intracranial planes tested for validity by evaluating inter-individual variability include the palatal, functional occlusal, mandibular, Y axis, nasion-pogonion, A point-B point [16], basion-nasion [15], and pterygomaxillary vertical [17]. All of these craniofacial planes have been shown to display variability as large as FH and SN.

With such inter-individual variability in craniofacial reference planes, one's ability to apply meaningful facial typing and analysis from one individual to another is limited. Therefore without a craniofacial reference plane with low variability, comparison of facial structures to current variable reference planes must be treated with caution. It is clearly evident that an SNA of 82° in two individuals does not represent the same degree of maxillary prognathism in both cases due to a difference in orientation of SN. In an attempt to account for this, other cephalometric analyses avoid the use of skeletal reference planes, such as in the Wits analysis. The Wits analysis simply compares the prognathism of the maxilla and mandible to each other, along the occlusal plane. Of course, the occlusal plane is prone to large angular inter-individual variability and this analysis is also not without its weaknesses.

It is, therefore, evident that the comparison of cephalometric analyses between two or more individuals is limited by the variation in reference planes (SN & FH etc) upon which the analyses are based. This questions the validity of the current use of cephalometric normal values, which are mean values derived from population studies.

Cephalometric analysis is not only used to compare an individual to a mean population sample but also to compare treatment and growth changes in one individual over time. This involves the process of superimposition. For superimposition to be meaningful, the fiducial reference plane should be easily identified, reliable, and maintain spatial orientation longitudinally.
However, a number of investigators have illustrated that specific errors associated with cephalometric superimposition can be attributed to growth and remodelling at the reference plane [43, 44] as well as to the method error associated with the reference plane [45]. It would appear that nasion drifts during growth and remodelling and additionally, is not always readily identifiable in the vertical plane [46]. However data on the longitudinal intra-individual change in reference plane orientation is minimal, probably because such changes are small, and less than the method error attempting to detect these changes.

The historic literature outlines a search for more effective craniofacial reference planes to make comparison between individuals more meaningful. Ideally, a valid cephalometric reference plane/system should have the following features: good reliability (low method error), good intra-individual reproducibility, low inter-individual variability, and average orientation close to true horizontal (HOR) or vertical (VER). HOR or VER represent a logical reference plane for inter-individual comparison.

In order to use HOR or VER in cephalometric analysis, a method of reproducible head orientation must be selected. Without such a method, inter-individual differences in craniofacial morphology will be masked by larger intra-individual differences in head orientation. A well known and commonly cited reproducible head orientation is that of "Natural Head Position" (NHP).

5.4 Natural Head Position

"Lorsqu' un home est debout et que son axe visual est horizontal il est dans l'attitude naturalle" Broca, 1862 [47].

5.4.1 Definitions

Natural Head Position

There are numerous definitions describing this orientation of the head. The first definition of head orientation in a "natural" position was first introduced by Broca [6] in 1862. This concept was put forward as a guideline for craniologists to orient dry skulls for analysis. When the above is translated, Broca defined the natural head position "when a man is standing and when his visual axis is horizontal, he is in the natural position [2]".

Natural head position (NHP) has been previously recorded by a subject looking into the distance or into a mirror. Such methods may not necessarily be a true physiological position, because head position is result of a dynamic, muscular controlled posture. In such cases, the term "natural head position" may actually be a misnomer. However, much of the orthodontic literature involving NHP describe registration of this head position by means of the subject looking into a mirror. This may be more appropriately titled a "visual guided head position" [48] or "mirror position" [49]. In essence, NHP is a standardised, reproducible head position with the subject's head erect and looking into a distant object. Such distant objects include the reflection of one's eyes in a mirror, light source at eye level or the horizon. It is assumed that this head orientation closely reflects the average physiological one adopted during daily life.

The standing position often used to record NHP has been described as “orthoposition”. Mølhave [50] in 1958 defined orthoposition as the intention position from standing to walking. This is a natural head posture adopted on the first step from standing to walking. Perhaps this implies a posture with more neck flexion than extension (i.e. the head postured down).

“Self balance position” is a concept introduced by Solow and Tallgren [7] in 1971. This method of head orientation was defined as “the subject’s own feeling of natural head balance”. This undoubtedly has an element of subjectivity and is open to subject interpretation. This investigation found less reproducibility in the self balance position, with a Dahlberg value of S(i) = 2.48°, as compared with the mirror guided head position, S(i) = 1.43°.

Natural Head Posture

This refers to the physiological relationship of the cranium to the cervical column. It is, therefore, dictated by the muscular posture and response to physiological and environmental conditions. Variation in head posture has been associated with respiratory function and craniofacial morphology [49, 51].

Schmidt [52] in 1876 stated that the natural posture of the head with the eyes focussed at the horizon was determined by muscular control. This may be consistent with Von Ihering’s findings who reported the greatest consistency in natural head position to be in “muscular and intelligent people” [24]. This muscular control is reflected by the angulation an individual’s head makes with the underlying cervical column supporting it. The first investigators to measure this were Solow and Tallgren [7] in 1971.

Natural Head Orientation

This orientation was first illustrated by Moorrees and Kean [2] who corrected those subjects with “tenseness” in their natural head position. “Natural head orientation” later described by Lundström and Lundström [3, 41] is defined as the head orientation of the subject perceived by the clinician, based on clinical experience, as the natural head position in a standing, relaxed body and head posture, when the subject is looking at a distant point at eye level. They advocated the use of a operator guided natural head orientation (NHO) to correct "unnatural" natural head position registrations.

However, Halazonetis [53] found that NHO was influenced by craniofacial morphology (particularly chin position), which resulted in an underestimation of the true skeletal discrepancy. Therefore, the validity of NHO may be questionable.

5.4.2 Factors Associated With Natural Head Position

NHP is dynamic in its nature. Individuals vary their head posture and NHP depending on the physiological and environmental demands. A number of factors appear to affect head posture. These include,

1. **Craniofacial Morphology**

   Björk [54, 55] in 1955 and 1960 and Brodie [56] in 1971 referred to the tendency of the head posture to camouflage its morphology. Bench [57] in 1963 reported that the neck was curved in brachycephalic types and relatively straight in dolicocephalic types. Solow and Tallgren [7, 58, 59] in their studies on natural head position, found that the craniofacial morphology was best related to the second vertebra odontoid process tangent. They showed that the extension group exhibited anterior inclination of the cervical column, increased anterior face height, decreased posterior face height, decreased anterior-posterior craniofacial dimensions, increased mandibular posterior inclination, and reduced nasopharyngeal space.

2. **Walking**

   The vast majority of literature pertaining to head posture and NHP relates to the static position while standing or sitting. However, it would seem that head posture is by no means static in real life, but a range of head orientations about a mean head orientation.

   Usumez and co-workers [60] in 2006, compared static head position with walking head position by means of eyewear inclinometer measurements. The head position of 50 subjects was compared during a “self balanced” head position and during a relaxed 5 minute walk. The mean walking head position was 4.6° tipped down compared with the mean static head position.

3. Respiratory Resistance

Early investigations by Woodside and Linder-Aronson [61] in 1979 reported on a group of children who were deemed to require adenoidectomy. They found head posture was extended or bent backward by 6° relative to true vertical in these children as compared with normal nasal breathing controls. This difference between intergroup head posture was no longer evident 1 month after adenoidectomy.

Vig, Shoferty and Philips [51] performed an investigation in manipulation of head posture by total nasal obstruction, visual feedback deprivation and a combination of the two. Total nasal obstruction by a swimmer nose clip resulted in an extension of the neck in all subjects.

Solow and co-workers [49] investigated this relationship in 1984 and found that on average, obstruction or reduced adequacy of the nasopharyngeal airway was associated with a larger craniocervical and craniovertical angulation. This is also reflected in other investigations [62].

Obstructive sleep apnoea has also been associated with head extension [63-65].

4. Rapid Maxillary Expansion

Tecco and co-workers [66] followed up head posture after RME therapy in 23 female subjects in 2005. They found a statistically significant increase of pm-Ad 2 (narrowest part of nasopharyngeal airway), a significant increase of the cervical lordosis angle, flexion of the head, and decrease in the craniocervical angulation.

In a similar investigation by McGuiness & McDonald [67] in 2006, 43 subjects were followed up immediately and 1 year after RME. No change in head posture was found immediately after expansion. One year post expansion, however, NSL/VER had reduced by 3.14°, OPT/HOR by 2.13° and CVT/HOR by 2.55°. The authors attribute this change to a change in mode of breathing from oral to nasal breathing. The mechanism of this change may be related to the soft tissue stretching hypothesis proposed by Solow and Kreiborg [68] (Figure 10).

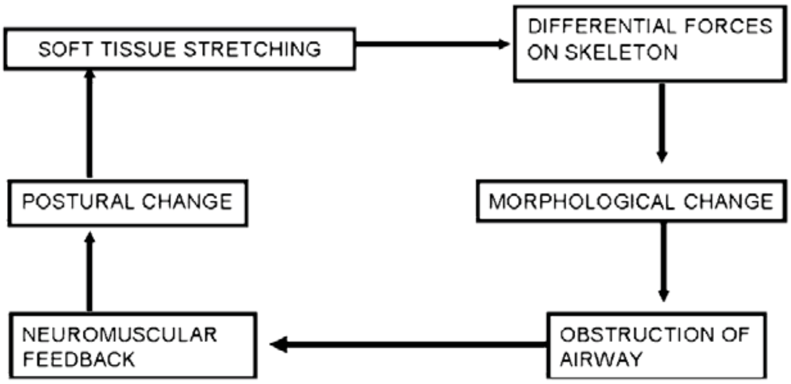


Figure 10. Soft tissue stretching hypothesis relating morphologic, respiratory and postural changes [68]

5. Orthognathic surgery

Savjani et al [69] in 2005 investigated the change in craniocervical angle after orthognathic surgery. 33 subjects underwent surgery that changed the vertical face height. The findings showed no change in head position (NSL/VER) but neck posture changed (NSL/OPT). However the authors concluded that this change in neck posture was not associated with surgery.

6. Functional appliance

Tecco and co-workers [70] assessed cervical spine posture after functional appliance therapy. Twenty female patients treated with FR-2 regulators were compared to 20 untreated Class II controls. The cervical lordosis angle (CVT/EVT) was significantly higher in the study group compared to the control group at the end of treatment, probably due to a significant backward inclination of the upper segment of the cervical column (OPTNer and CVTNer) in the treated group from pre to post treatment. There was no significant change in the lower segment of the cervical column inclination (EVT/VER).

7. Craniomandibular disorder

In 2005, Valenzuela et al.[71] investigated head posture by means of the craniovertebral angle formed by the McGregor plane to the odontoid plane. The sample of 50 subjects were divided into the following three groups based on the size of this angle: head extension (less than 95 degrees); an arbitrarily assigned normal head posture (between 95 degrees and 106 degrees); and head flexion (more than 106 degrees). No association was found with these head posture groups and the incidence of CMD.

8. **Altered vision**

   Fjellvang and Solow [72] investigated 30 blind from birth subjects (aged between 15 and 35 years) and a control of 171 dental students (aged between 22 and 30 years). On average, blind subjects showed more variation in head posture. Additionally, the head was tilted 4.3° down in comparison to the control group, and the neck was inclined 4.5° more forward compared to the control group. The craniocervical angle was similar in both groups.

5.4.3 Practical Applications of Natural Head Position

1. **Cephalometric Analysis**

   Several researchers have argued that NHP is a logical reference system and best orientation position for the evaluation of craniofacial morphology. The Moorrees Mesh analysis which was previously based on the orientation of a mesh oriented along SN [73] was subsequently adapted to the use of true horizontal [2, 74] (Figure 11).

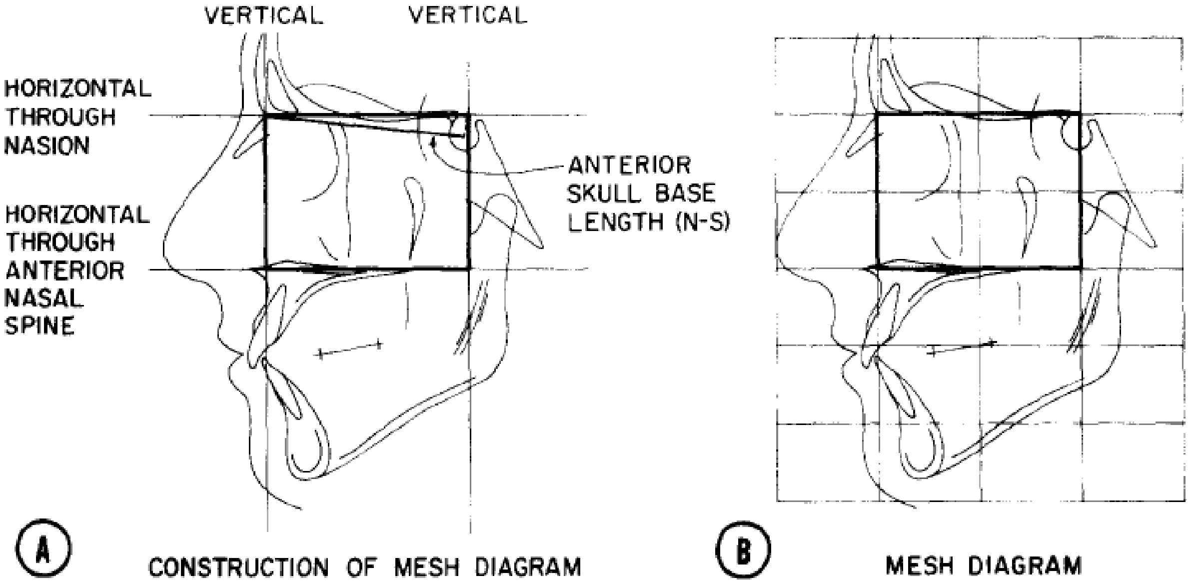


Figure 11. Moorrees mesh analysis oriented on true horizontal and vertical [74]

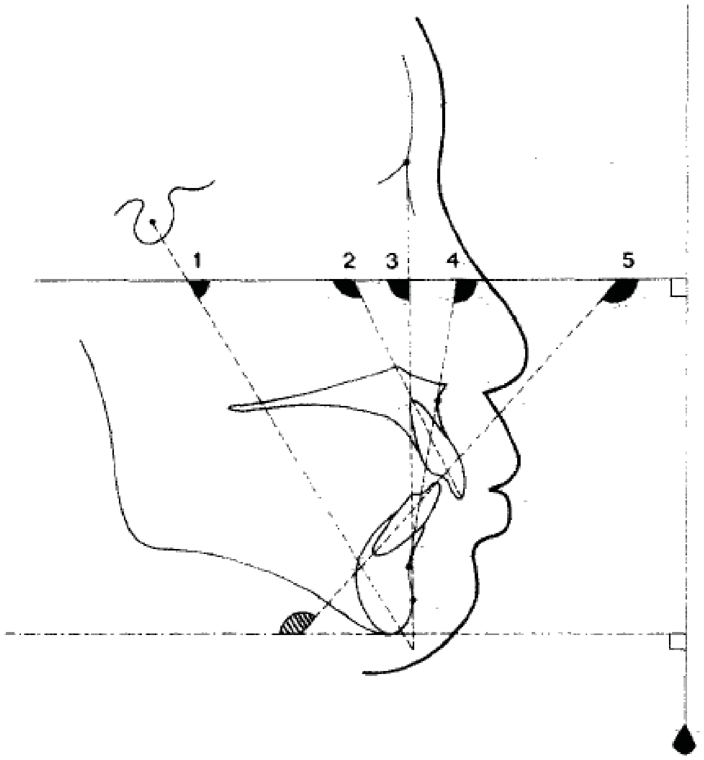


Figure 12. Five factor summary analysis of Cooke & Wei [16]

In 1988. Cooke & Wei [16] proposed an angular cephalometric analysis based on the use of true horizontal (Figure 12). They found that although previous cephalometric analyses illustrated Chinese males to be on average Class II skeletal compared to Caucasian males, their analysis based on NHP found them to be Class III on average. The use of NHP was advocated as being a true life representation and more clinically meaningful.

2. Cephalometric Superimpositions

Intuitively, one would imagine that the intra-individual reproducibility of NHP on two or more successive occasions would be inferior than the degree of change in a reference plane of an individual over time and, therefore, restricting the use of NHP in cranial base superimposition. However, this has not been shown to be the case.

Goel and coworkers [75] compared a new method of cranial base superimposition based on NHP and Viazis' triangle. The new method employed cranial base superimposition using the anterior wall of sella and true vertical and horizontal passing though this point (Figure 13). Although no statistical differences were found, the measurement methods employed might be questionable, and the authors alluded to the measured changes being small but with high standard deviations.

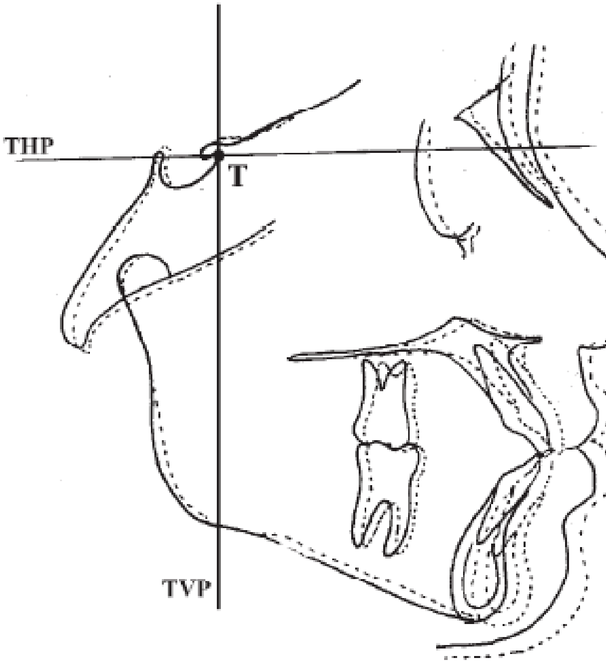


Figure 13. Cranial base superimposition on true vertical and horizontal lines [75]

5.5 Methods of Recording Natural Head Position

Broca's definition of natural head position in 1862 provided the basis for subsequent investigators to record natural head position where the subject "is standing and his visual axis is horizontal" [76].

The use of a true vertical or horizontal extracranial reference planes in cephalometric analysis requires a head orientation that is easily applied, reproducible, and also the best representation of the head orientation in true life. Additionally, the recorded head position should relate the cranium and cervical spine in a normal and physiologically habitual position. This would require reproducible coordination of the head and neck musculature to produce such a position.

One of the first techniques for recording NHP was described by Von Baer [77] in 1861. The subjects were instructed to sit comfortably and relaxed on a stool. While doing so they were asked to look in the image of their eyes in a round mirror located at the same level as the pupils of their eyes. Most subsequent investigations have used an adaptation of this original technique. In 1912, Luthy [25], a well known anthropologist, also used a mirror technique in front of a seated subject who was instructed to look into their own eyes.

The first orthodontic publication relating to NHP was in the landmark paper by Downs [5] in 1956. This paper set out to clarify harmonious dentofacial profiles from inharmonious ones providing a logical means of soft tissue profile typing. Downs photographed 100 children's lateral head profiles while standing and looking at their own eyes into a mirror. He proposed having the subject standing and looking at a distant object illustrated that discrepancies between facial typing disappear when a correction is made for those persons whose Frankfort plane is not horizontal. In other words, Downs adjusted his normative values for prognathism by the amount of deviation of the reference Frankfort Horizontal from true horizontal.

Moorrees and Kean [2] in 1958 published another key paper describing a similar method of NHP registration. They adapted the method of head registration used by Von Baer [77] to record the patient in NHP radiographically. The subjects were placed in NHP within the cephalostat prior to lateral head radiograph exposures. The resultant film captured NHP with a vertical stainless steel wire on the radiograph cassette providing a true vertical reference plane. With subjects seated, head orientation was guided by a mirror 100mm in diameter and attached to the wall 170 cm away at the level of the transmeatal axis. The cephalostat used was modified from the original Broadbent [1] cephalostat to have no ear plug engagement and the radiograph cassette was oriented with a sprit level to the horizontal and had a wire running vertically down it. Occasionally, the clinician manually adjusted the head orientation if they felt there was a significant discrepancy to NHP.

Cleall [9] in 1965 recorded form and function during swallowing with subjects in natural head position by placing a small light at eye level 5 feet in front of the subjects. Subjects looked into this light while standing in a relaxed position.

In 1968, Mills [78] published a grid method of assessing lateral head radiographs in which the subjects were recorded in natural head position. Mills, guided by the works of Moorrees and Kean, used a very similar radiographic technique (Figure 14), except that the stool, not the cephalostat was adjusted for height.

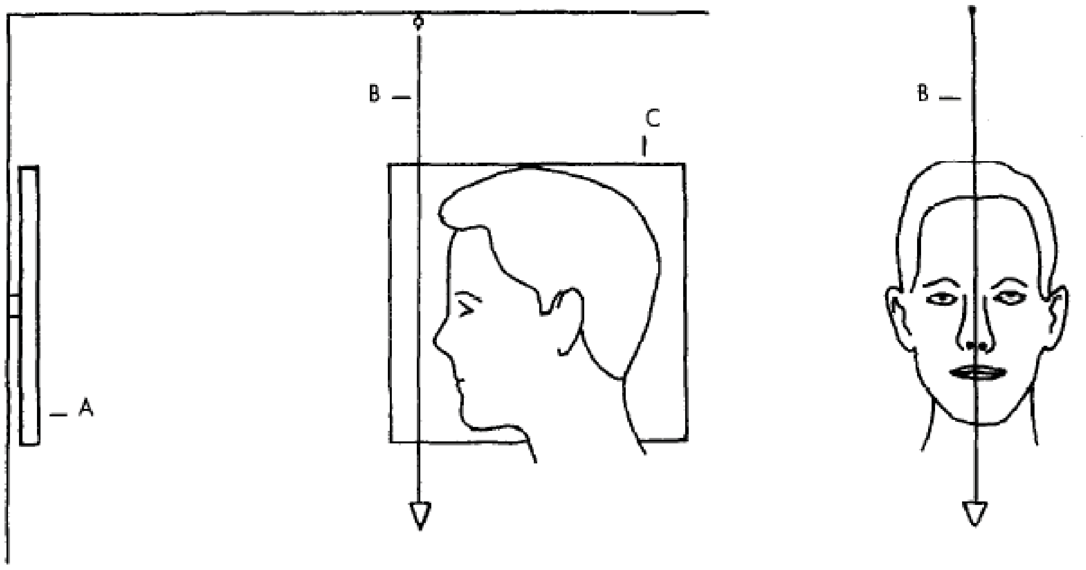


Figure 14. Natural head position registration during lateral head radiograph exposure. A. Mirror, B. Plumb line, C. Cassette [78]

In 1971, Solow and Tallgren [7] published a paper comparing the mirror guided NHP and the self balance head position during lateral head radiography. 120 subjects were set up in the modified cephalostat with striking similarity to that of Moorrees and Kean [2]. All subjects were standing in "orthoposition" [79] which was achieved by subjects walking on the spot. The self balance position film exposure was obtained by the subject's own feeling of natural head balance after head bending exercises (tilting their head back and forth with decreasing amplitude). This procedure was repeated in the cephalostat such that the external auditory meati corresponded with the vertical plane of the ear rods (Figure 15). The head holder was then lowered carefully to ear level, inserted, and the film exposed. The mirror NHP was then obtained by subjects looking into their eyes on a 20x100 cm mirror 137 cm away from the plane of the ear rods. A second film was then exposed. Subsequent authors have adapted this method of NHP registration [12-14, 16, 35, 36, 38-40, 42, 80].

NOTE: This figure is included on page 38 of the print copy of the thesis held in the University of Adelaide Library.

Figure 15. Self balance position in the modified cephalostat prior to film exposure[7]

Siersbæk-Nielsen and Solow[35] in 1982 used a combination of the mirror and self balance methods in a study on inter-examiner variability of head posture recorded by dental auxiliaries. For this study orthoposition was obtained in 30 subjects by walking on the spot and decreasing amplitudes of head tilting performed until a position of self balance was obtained. Following this, the ear rods of the cephalostat were inserted and the patients instructed to look at their eyes in a mirror, then the film was exposed.

Showfety[10] in 1983 was the first to introduce a fluid level device as a means of reproducing a subject's NHP to the cephalostat when taking a lateral head film exposure. This device utilises the surface of liquid being always horizontal in a non-accelerating hydrostatic system such that the surface aligns perpendicular to the force of gravity. This small fluid device was mounted on a small pivot bracket and attached to the subject's temple with double sided tape (Figure 16). At this point, NHP was obtained in 28 subjects standing (in the orthoposition) and looking into the distance. The fluid level is then set at horizontal to correspond with the NHP. Then the subject is instructed to walk into the cephalostat, their head inclination readjusted such that the fluid level is horizontal, then the film exposed.

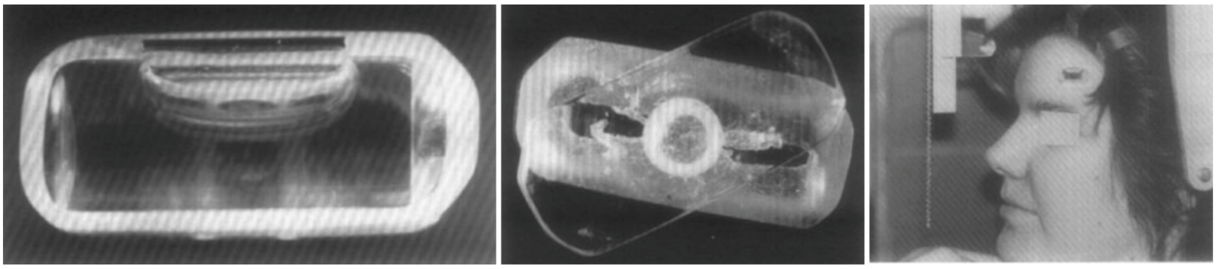


Figure 16. The Showfety fluid level, pivot hinge, and fluid level fixed to subject's temple [10]

Sandham [38] in 1988 used a method for recording NHP quite similar to that of Siersbæk-Nielsen and Solow [35]. This NHP protocol included 12 subjects attaining self balance position in the cephalostat, insertion of the ear rods, and finally looking at a reflection of their own eyes in a mirror at least 2 m away. The rehearsal stage included the patient walking on the spot, then raising and lowering the shoulders several times to relax.

Following on from previous authors who used a photographic recording of NHP [4, 81], Lundström and Lundström in 1992 [15] were the first to publish a photographic technique for transferring NHP to a lateral cephalometric film. This technique involved 52 subjects acquiring a NHP by standing in Mølhave's orthoposition [79], looking into their own eyes on a vertical mirror 1 m away, and teeth in light centric occlusion. A plumb line was used to display true vertical and lateral head photographs were taken. A horizontal line perpendicular to the vertical plumb line was transferred from each photograph to the corresponding lateral head radiograph [82]. This method of transfer involved firstly measuring the angle (a) of soft tissue nasion-pogonion (N'-Pg') to the true horizontal reference plane, HOR on the photograph (Figure 17). A second angle (b) was recorded from SN/N'-Pg on the radiograph. The angle (c) of SN to HOR was then calculated using simple mathematics as below.

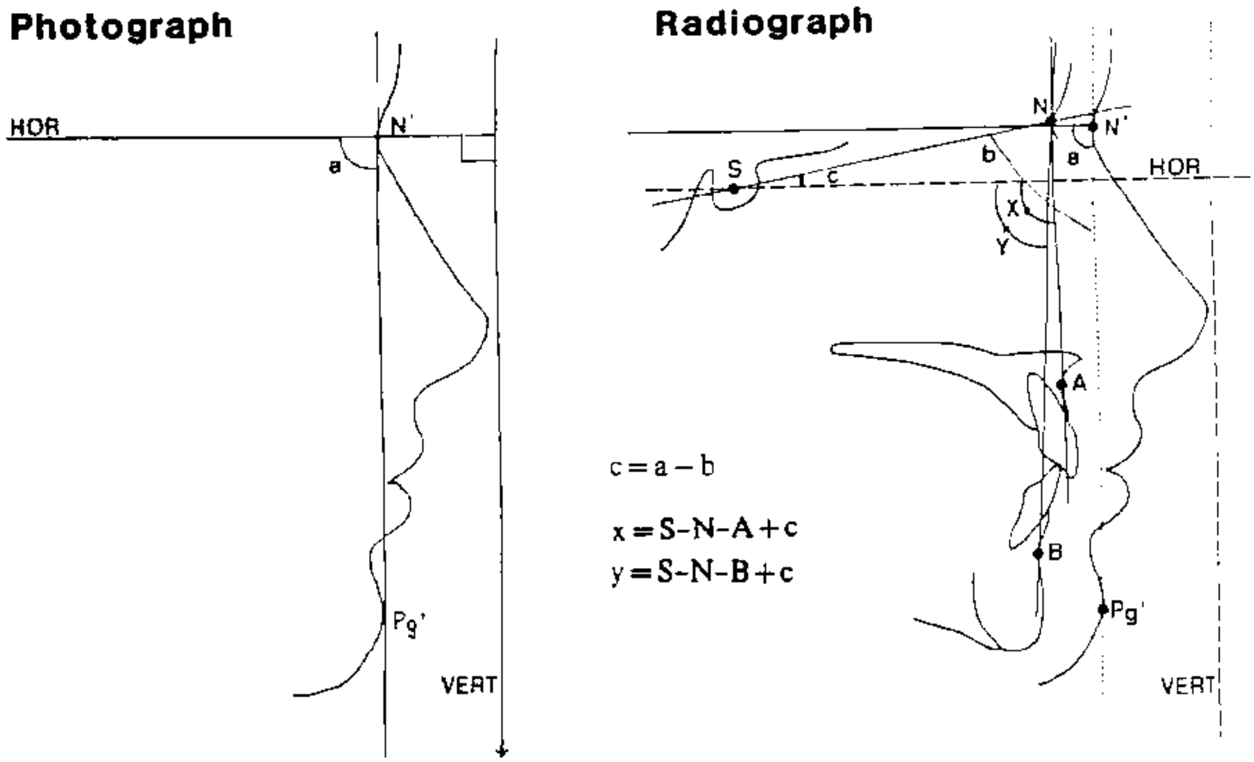


Figure 17. The transfer of true horizontal (HOR) from photograph to radiograph [15]

Lundström and Lundström [3] furthered their investigations in this area by introducing the concept of "natural head orientation" as a method of registering natural head position. NHO refers to a head orientation perceived by the clinician, based on general experience, as the natural head position in a standing, relaxed body and head posture, when the subject is looking at a distant point at eye level. Their sample of 27 patients 10 to 14 years old were assessed in NHO and mirror guided photographic method on two occasions, 3 weeks apart. They found that NHO was also a valid method of registering natural head position.

Preston in 1997 [11] investigated the relationship between NHP and head posture measured during walking by the use of an inclinometer. The inclinometer is a commercially available device that uses a contactless precision potentiometer to continuously measure changes in inclination around a single axis of rotation. On a pair of spectacles, the inclinometer was fixed to one arm and a counterbalanced weight on the other arm. Then NHP was recorded with subjects wearing the spectacles using the protocol outlined by Sandham [38]. Continuous recording of head posture then took place with the subjects walking in a large room with bare walls, no direct vision to the outside, and good artificial lighting. Once the subject felt comfortable walking a 5 minute recording was taken.

Usumez and Orhan in 2001 [83] expanded on the method outlined by Preston [11] by placing an inclinometer for pitch on one arm of the spectacles, and another inclinometer for roll on the other arm (Figure 18). 20 subjects obtained a position of self balance as described by Solow and Tallgren [7]. This was done 10 times at one minute intervals while subjects stood in front of a wall mounted mirror 1 m away. They were instructed to look into their eyes while wearing the spectacles.

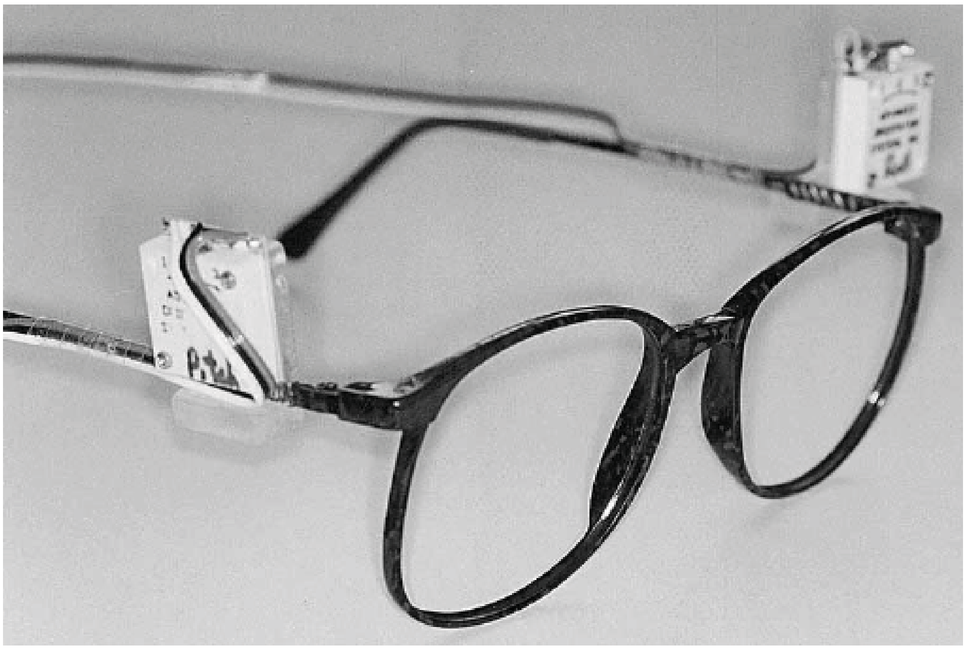


Figure 18. Two inclinometers for pitch and roll fixed to a pair of spectacles [83]

In summary, it is evident that since the early work of Von Baer [77], the mirror guided visual technique of obtaining NHP in one form or another seems to be the accepted technique. A widely accepted mirror guided NHP registration technique is that of Solow and Tallgren [7]. Some authors have increased the complexity of the mirror technique by adding fluid levels and spectacles. This may adversely affect the results by inadvertently distracting the subjects. If minimising distractions is determined to be important, the removal of ear plugs when exposing the lateral head radiograph appears to be a valid technique. Even more so, the photographic technique by Lundström and Lundström [82] will remove the distractions of a radiographic cephalostat and may be the most promising technique. For this reason, the present study will use a photographic method of natural head position registration in combination with the subject preparation outlined by Solow and Tallgren [7]. Regardless of the method of NHP registration, of much greater importance is whether the method facilitates reproducible results. Therefore, reproducibility of NHP must be clearly outlined, to justify the use of natural head position and a true vertical or horizontal reference plane in cephalometric analysis.

5.6 Reproducibility of Natural Head Position

The reproducibility of NHP is effectively describes the intra-individual variability of recorded head position on two or more successive occasions. It is normally quantified by observing the angular difference between HOR/VER and a chosen reference plane on two occasions. For the use of NHP to be valid, the intra-individual variability of NHP must be less than the inter-individual variability of other craniofacial reference planes when both compared to a true vertical plumb line.

Surprisingly, most of the NHP method error (or reproducibility) studies show similar results.

Schmidt [84] in 1876 investigated head balance stating that the natural position of the head with the eyes focussed at the horizon was determined by muscular control. Ten repeated observations of 20 individuals made by him and five other observers showed that head position could be reproduced with little variability when corrections were made in the self-position if necessary. In his observations, Schmidt used a wooden frame to which a protractor and plumb line were attached. The constancy of head position was reported to be greatest in “muscular and intelligent people” [2].

One of the first papers to objectively assess reproducibility of NHP was Bjern in 1957 [4]. After registering 35 subjects in NHP on three separate occasions, a method error analysis was carried out. The difference between the maximum and minimum values of the 3 determinations of the angle SN/HOR was calculated for standing subjects, and the resultant mean error was 2.26° with a standard deviation of 1.34°. The method error or reproducibility of the sitting position was 2.73° with a standard deviation of 1.62°.

In 1958, Moorrees and Kean [2] tested the hypothesis that NHP of man is relatively constant. This investigation was primarily undertaken in response to the findings of Björk [33] who illustrated the unreliability of craniofacial reference lines. Moorrees and Kean related NHP to the extracranial reference plane of true vertical and tested the intra-individual reproducibility of NHP by means of a method error study. All subjects were North American females divided into one group of 66 freshmen students and 61 senior students. Lateral head radiographs were taken in a seated position with head unsupported and looking at the reflection of their own eyes in a mirror. Two radiographs were taken of each subject with a 1 week time interval between them. The variability of head position at successive observations was determined by statistical analysis of the difference in the angle SN/VER according to the Dahlberg formula [2],

$$\text{S.D.}_{\text{head position}} = \sqrt{\frac{\text{sum of differences}^2}{2\text{n}}}$$

The Dahlberg value for NHP reproducibility in the 66 freshmen students was 2.05°. In the 61 senior students the Dahlberg value was 1.54°. These results are remarkably similar to Bjern's [4]. The increased accuracy of the second group was explained by the fact that unnatural head tilting was corrected by the operator in the second sample group ("corrected head position" [84]).

The paper by Solow and Tallgren in 1971 [7] investigated the reproducibility of self-balance position and the mirror guided NHP in 120 Danish male students, 22 to 30 years old. In this study it was found that in the mirror position, the subject's heads were generally held higher than in the self-balance position. Additionally, it was shown that both head positions could be reproduced without systematic error. The NHP reproducibility in the self-balance and mirror guided head position were

Dahlberg values of 2.48° and 1.43° respectively. These values include the method error of transferring the reference points, which was found to remarkably low.

In the study by Siersbæk-Nielsen and Solow[35], the reliability of a method that dental auxiliaries could use for routine recording of NHP was investigated. The method of NHP registration was guided by the protocol of Solow and Tallgren[7] involving a self-balance position followed by mirror guidance. Thirty subjects aged between 6 and 15 years of age were recorded in NHP at two separate occasions. The method error for these separate occasions was calculated to be a Dahlberg value of 2.3° for head posture as measured by SN/VER, 3.1° for the cervical inclination (OPT/HOR) and 3.4° for the craniocervical angulation (NSL/OPT) (Figure 19). The authors felt this method yielded sufficient reproducibility to justify the use of NHP in the orthodontic clinic.

Figure 19. The craniofacial reference planes used to test the method error[7]

The reproducibility of head posture registration in lateral cephalometric radiographs was also investigated by Sandham [38] in 1988. This study tested 12 subjects, 8 male and 4 female aged 8 to 15 years. The technique used was that described by Solow and Tallgren [7] which used walking, decreasing amplitude of head tilting and finally a mirror reflection. The radiographs were taken by a single radiographer, with a time lapse of at least one hour between first and second films. The error of the method for head position to a true vertical reference plane (NSL/VER) was a Dahlberg value of 3.2°, for the craniocervical angulation (NSL/OPT) 2.6° and for the cervical vertebra tangent (NSL/CVT) 2.4° (Figure 19). This study demonstrates that a reproducible head posture position exists and can be recorded with a method error of only a few degrees.

Cole [36] in 1988 studied the reproducibility of NHP using a fluid level device described by Showfety et al [85]. A sample of 8 subjects were recorded in NHP on two occasions 6 months apart. The reproducibility of SN to the true vertical reference line (VER) was 2.18° whilst the reproducibility of SN to the cervical vertebra tangent was 4.20°. These values were similar to those obtained by Solow and Tallgren [7] and Siersbæk-Nielsen and Solow [35].

Cooke et al [39] published similar results in a comprehensive study of 217 twelve year old Chinese children in Hong Kong. The method of NHP followed the orthoposition of Mølhave [79] and exercise/mirror protocol of Solow and Tallgren [7]. Their findings showed that NHP reproducibility was better with a mirror (method error 1.9°) than without a mirror (method error 2.7°) but no significant differences were found when recordings were taken with and without ear posts. Cooke et al [39] were the first to investigate the longitudinal reproducibility of NHP with future papers showing longer term results. Errors between recordings on the same day averaged 1.9° compared to 2.4° when three to six months had elapsed between radiographs.

In 1990, Cooke[12] followed up the original sample from the 1988 study [39] by publishing the results of a five-year longitudinal evaluation of reproducibility of NHP. Cooke's work showed that NHP reproducibility deteriorated over the time but showed signs of stabilizing after 1 to 1.5 years. After one to two hours the method error was 1.93°, after three to six months 2.34°, and 3.04° after two to five years. The individual variability of NHP also increased over time. This author suggests that further longitudinal studies are required to determine if NHP reproducibility deteriorates further over time, but still its variability remains significantly less than the variability of intracranial reference planes to a vertical plumb line. The authors therefore still advocate the use of NHP and true vertical reference planes in cephalometric analysis.

Lundström and Lundström [32] in 1992 used a combined photographic and radiographic technique when evaluating the NHP of 52 children aged 10 to 14 years old. Two lateral photographs were taken with the subjects in NHP at a time interval that was not reported. The published NHP reproducibility for males was a Dahlberg value of 1.8°. Interestingly, a systematic difference of 1.0° ($p<0.01$) was found between the first and second recordings of NHP, indicating a tendency for children to raise their head slightly at the second recording.

Lundström and Lundström [41] expanded on the previous work in a paper published in 1995. The 79 twelve year old subjects were recorded in the mirror guided NHP. If a radiograph appeared to the authors to not represent NHP then the authors used their own clinical judgment to reorientate a radiograph in a position which they thought best represented NHP, termed natural head orientation (NHO). These authors found that NHP variability was 5.2° for boys and 4.0° for girls verses NHO variability of 3.6° for boys and 3.0° for girls. The authors recommend that NHO was the least variable head position and a valuable clinical tool.

In a further study on NHO, Lundström and Lundström [3] in 1995, the accuracy and validity of NHO was assessed. Lateral profile photographs of 27 orthodontic patients, aged 10 to 14 years were taken, these were then cut into circular shapes and the orientation of these photographs in natural head orientation was examined by four investigators. Findings among four investigators showed a high correlation in orientating these profile photographs in estimated NHP, and also include correlation ($r=0.57$-0.84) in head orientation after a three-week period. The authors suggest that clinicians and auxiliary personnel can be trained to make critical judgment of the recorded NHP and correct head orientation, whenever indicated, to enhance the reliability of cephalometric analysis in clinical practice and research.

In 1999, Peng and Cooke [13] published the longest term reproducibility results to date. They set out to investigate the long-term clinical reproducibility of NHP and whether it was greater than the variability of conventional reference planes with respect to true vertical. Of the original 12 year old sample in Cooke's 1988 study [39], 20 subjects were followed up and had repeated cephalograms taken 15 years after the initial lateral head radiograph. The method error (reproducibility of NHP) after 15 years was 2.2 °, which compared favourably with the five-year reproducibility (method error 3.0°) and the five to ten minute reproducibility (method error 1.9°). The intra-individual variability of natural head posture increased slightly over the time. After 15 years the intra-individual variability of NHP (4.8°) remains significantly less than the inter-individual variability of intracranial reference planes to true vertical. The authors concluded that cephalometric analyses based on NHP therefore remains valid over long periods of time.

Bister and co-workers [86] investigated the reproducibility of NHP in 2002. The Dahlberg value of NHP after a 1 year interval was 2.99° (VER/V-line) and 3.24° (VER/E-line) where V-line was soft tissue nasion-subnasale and E-line was that of the Ricketts analysis.

The Table 2 below summarises the investigations observing NHP reproducibility.

Table 2. Literature summary of reproducibility of natural head position

Author and Year	n	S(i)	Double determinations (°) Mean range	SD range
Bjern, 1957 [4]	35		2.26	1.34
Moorrees & Kean, 1958 [2]	66	2.05		
Carlsoo & Leijon, 1960 [87]	17	4.6		
Solow & Tallgren, 1971 [7]	21	1.43		
Fränkel, 1980 [88]	923		2.44	2.03
Foster, 1981 [89]	8		4.1	
Siersbæk-Nielsen & Solow, 1982 [35]	30	2.25		
McWilliam & Rausen, 1982 [81]	15	1.8		
Lyuk, 1986 [90]	18	4.9		
Cole, 1988 [36]	8	2.18		
Cooke & Wei, 1988 [16]	30	1.9		
Sandham, 1988 [38]	12	3.2		
Cooke, 1990 [12]	30	3.04		
Lundström & Lundström, 1992 [15]	27	1.8		
Huggare, 1993 [40]	33	1.6		
Peng & Cooke, 1999 [13]	20	2.23		
Bister et al, 2002 [86]	65	3.24		
Usumez & Orhan, 2003 [91]	20	1.1		

In summary, there is substantial evidence in the orthodontic literature to suggest that when compared to true horizontal, NHP is clinically reproducible. This has been summarised in table form above (Table 2). From the early works in the 1950's until the present, all studies of NHP reproducibility come to very similar results. This low variability of mirror guided head position has not only been proven in the short term, but over significantly longer periods up to 15 years. However, before accepting the validity of such results, one must bear in mind that most reproducibility studies compare sella-nasion (SN) to true vertical. Therefore the reproducibility result is only valid if there is minimal remodelling of sella and nasion such that the relative orientation of SN does not change over time.

The other important feature of NHP is the intra-individual reproducibility has quite clearly been shown to be significantly less than the inter-individual variability of conventional craniofacial reference planes, when both related to true vertical. This is the primary basis for the use of NHP (and a true vertical/horizontal) in cephalometric analysis because it is effectively, a more stable reference plane. And therefore, will provide a more meaningful cephalometric analysis and no doubt, more clinically relevant diagnosis of skeletofacial discrepancies.

5.7 Conclusion

Cephalometric analysis has shortcomings such as the quality of reference planes used to measure craniofacial morphology. When compared to a true vertical reference plane, planes such as FH and SN illustrate inter-individual variability of 3° to 9°.

The use of NHP as a craniofacial system appears to represent a valid replacement of conventional craniofacial reference planes because of its true life representation of head orientation, its ease of registration, and its good intra-individual reproducibility when related to true vertical. NHP can reliably be reproduced within 2-3° which is less than the inter-individual variability of sella-nasion or Frankfort Horizontal in relation to true horizontal. The most accepted natural head registration protocol is a mirror-guided technique, while standing in orthoposition [79] with some neck bending exercises [7]. This technique, therefore, was adopted in the present study.

There are, however, some limitations to the use of NHP that must be considered. All the promising results for reproducibility of NHP assume that the craniofacial reference plane (usually SN) compared to true vertical has no method error when imaging, tracing and measuring. This most likely has little significance in the short term. However, for long term reproducibility of NHP, it is unlikely that SN has remained stable. It is hard to say how much sella or nasion have moved or remodelled in that period of time without the use of implants in stable structures. Peng and Cooke [13] used an anterior cranial base superimposition of the stable structures for their 15 year follow up. However, there may have been some difficulties in their superimpositions of the 12 year old and 27 year old radiographs due to growth. In essence, the long term reproducibility of NHP should be accepted, but with caution.

The search for an ideal craniofacial reference plane with low variability has continued for more than 200 years. The use of true vertical from the less variable NHP is one step closer to ideal but is not without its limitations. The inter-individual variability of a number of planes such as FH and SN has been investigated, illustrating conclusively, that intra-individual NHP reproducibility is less than the inter-individual variability of these craniofacial reference planes. No studies to date have investigated the variability of Krogman Walker line (KW line), neutral horizontal axis (NHA), foramen magnum line (FML) or posterior maxillary plane (PM plane) to true horizontal. Observing the variability of a range of planes to HOR including these formed the basis of the present study.

6. Aims

The present study aimed to establish a photographic protocol for recording NHP and to perform a cephalometric analysis to evaluate the variability of craniofacial reference planes in relation to true horizontal.

The specific aims were:

1. To provide a critical literature review with respect to the history, significance and use of natural head position in orthodontics. Also to outline the literature involving the variability of craniofacial reference planes.
2. To establish a photographic rig suitable for consistent and accurate registration of subjects in natural head position.
3. To establish a photographic protocol for photographically recording subjects in natural head position.
4. To acquire a sample of subjects recorded photographically in natural head position on two separate occasions.
5. To establish a method of transferring a true vertical plumb line from a lateral head photograph to its corresponding lateral head cephalogram.
6. To apply appropriate cephalometric and statistical analysis to evaluate the inter-individual variability of craniofacial reference planes to true horizontal and the intra-individual reproducibility of NHP.
7. To test the hypothesis stated in section 6.1.

6.1 Hypothesis

There is a craniofacial reference plane with less inter-individual variability than the intra-individual reproducibility of natural head position when both are related to a true horizontal.

7. Materials and Methods

7.1 Subject Sample

7.1.1 Inclusion Criteria

The sample for the present study included 67 consecutive subjects screened, assessed for orthodontic treatment or undergoing orthodontic treatment at the Orthodontic Department, Adelaide Dental Hospital, Australia. 10 subjects were excluded as per the criteria outlined in Section 7.1.2. The remaining 57 subjects were included in the present study on the basis of the following,

- Informed consent as outlined in Section 7.2 was obtained from the subject and the subject's parent.
- Subjects were aged between 12 and 18 years.
- A lateral head radiograph was taken as a part of the subject's orthodontic care.
- A first lateral head photograph (T1) taken in NHP was obtained within 1.5 months of the lateral head radiograph.
- A second lateral head photograph (T2) was taken in NHP 1 to 5 months after the first photograph (T1)
- The sample was collected prospectively and in a consecutive non-biased fashion as a part of the subject's orthodontic care appointments to minimise the participation problems and dropout rate. This approach enabled recruitment of a diverse range of craniofacial patterns.

7.1.2 Exclusion Criteria

The subjects excluded from the original sample satisfied the following criteria,

- The first lateral head photograph was taken more than 1.5 months prior to or following the lateral head radiograph.

- The second lateral head photograph was taken more than 6 months after the lateral head radiograph. The above two criteria were set to minimise problems with the vertical plumb line transfer process which relies on the use of the nose profile. Should the nose grow significantly, then the original lateral cephalograph tracing may not be adequately superimposed on the lateral head photograph.
- The lateral head radiograph did not include all the required anatomical features in Section 7.8.2.

7.1.3 Sample Size Estimation

Prior to collection of subjects for the present study, a power test was carried out to determine an adequate sample size. A statistical power test calculates the probability of not committing a type II statistical error (β) at a predetermined significance level (α). The Lundström & Lundström [15] data was used for power testing. This article observed a mean and standard deviation for SN/HOR of $\bar{x} = 3.8°$ and $\sigma = 5.3°$ respectively (N=52 subjects). This standard deviation is assumed to be a true estimate of the population standard deviation to perform the test.

The power (*P*) to detect a clinically significant change (arbitrarily assigned as 2°) at the α=0.05 significance level, is 0.80 when the chosen sample size is *n*=55. The calculations are outlined in Appendix 11.3.1. In short, if one sets the minimum power to be 0.80, then a minimum sample size of 55 subjects must be collected for adequate statistical analysis.

Alternatively, one could determine the sample size required to yield a particular power level at a given test significance. If one required a 90% power level (i.e., a 10% chance of committing a type II error) at the $p<0.05$ level of significance, then using the data above the required sample size, *n*, would be 91 subjects (Appendix 11.3.1).

For a power of 80%, the required sample size, *n*, would be 55 subjects (Appendix 11.3.1).

7.2 Ethics Approval

An application of human ethics approval was submitted to the University of Adelaide Human Research and Ethics Committee in August 2005. This application included,

- A research protocol outlining a title, literature review, aims and proposed methods (2 pages)
- A draft research information sheet (1 page)
- A draft consent form for adults and children (1 page each)

After feedback and modification of the research information sheet and consent forms, ethics approval was received in September 2005 from Ms Sabine Schreiber, Secretary of the Human Research and Ethics Committee, University of Adelaide. Approval number H-136-2005.

The proposed methods complied with the following,

- National Health and Medical Research Council (NHMRC) National Statement on Ethical Conduct in Research Involving Humans (1999)
- National Health and Medical Research Council (NHMRC) Values and Ethics - Guidelines for Ethical Conduct in Aboriginal and Torres Strait Islander Health Research
- National Health and Medical Research Council (NHMRC) Guidelines Under section 95 of the *Privacy Act 1988* National Health and Medical Research Council (NHMRC) Guidelines approved under Section 95A of the *Privacy Act 1988*

And the research carried out in the present study complied with the,

- Joint National Health and Medical Research Council (NHMRC)/ Australian Vice-Chancellors' Committee (AVCC) Statement and Guidelines on Research Practice (1997)

7.3 Informed Consent

In accordance with the guidelines set out by the University of Adelaide Human Research Ethics Committee, informed consent for participation in the present study was acquired from the subject's and their parents after satisfying the following requirements,

1. A detailed verbal explanation of the present study which covered all the points outlined in Appendix 11.1.1.

2. Each subject received a summarised written form of this explanation (Appendix 11.1.1) and a Human Research Ethics Committee Independent Complaints form (Appendix 11.1.2)

3. Each parent received a summarised written form of this explanation (Appendix 11.1.1) and a Human Research Ethics Committee Independent Complaints form (Appendix 11.1.2)

4. Each subject filled out the Child Consent Form (Appendix 11.1.3) to individually consent to participate in the present study.

5. Each parent filled out the Adult Consent Form (Appendix 11.1.4) consenting to allow the participation of their child in the present study.

All consent forms were photocopied and made available to the subjects and parents for their personal records.

7.4 Radiography

A single lateral head radiograph was obtained and used for each subject in the present study (Figure 20). Lateral head radiographs used in this present study were all obtained from the Radiography Department, ground floor, Adelaide Dental Hospital. All lateral head radiographs are taken with the same machine, OrthoCEPH OC100 (Instrumentarium Imaging). The settings for lateral head radiographs were as follows,

Voltage	77 kV
Current	12 mA
Exposure time	0.4 - 0.5 seconds

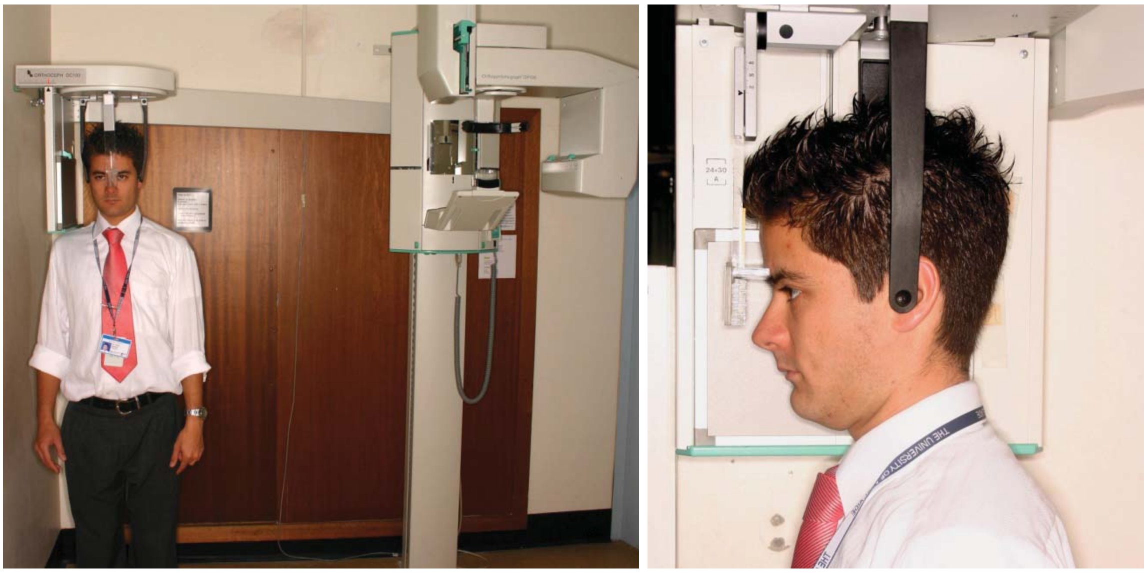


Figure 20. Patient positioning in OrthoCEPH machine. Frontal and lateral views. Note the effect of the subject having to tilt the head down

Two forms of radiographic image capture were used by the Radiology Department due to equipment upgrade during the course of the present study,

1. Radiographic film (5 subjects) – these were large in size and allowed all skull anatomy to fit with ease.
2. Digital phosphor plate (52 subjects) – these plates were considerably smaller and, therefore, required to be taken in landscape to capture the base of the skull. The subjects were also requested to tilt their head down to include the

anterior cranial base. It is worth noting how the chin-throat tissue bunching occurs with inferior head tilt. This will obviously affect the soft tissue profile in this area.

The radiographic protocol did not register the subject in natural head position. It was as follows,

1. Patient requested to step forward into cephalostat
2. Bilateral ear plugs inserted into external auditory meati
3. Teeth fully together and lips relaxed.
4. Head tilted down for those 52 subjects with the phosphor plate exposure.

7.5 Photographic Setup

7.5.1 Equipment

The equipment utilized to photographically record natural head position was selected to be able to produce consistent lateral head photographic images. The equipment selected was as follows,

a) **Photographic Tripod** – Manfrotto pro tripod black 055 PROB (65cm – 176cm, 2.4kg) with 141RC head. Positioned 2.40m away from subject. Variable height such that a directly perpendicular lateral head image can be consistently and accurately obtained. This was of sufficient size and weight to produce accurate and reproducible images.

b) **SLR Digital Camera** - Canon 300D body, Canon macro lens EF 100mm 1:2.8 ultrasonic, Canon macro ring lite MR-14EX.

c) **Mirror** – 1000 mm x 200 mm x 3 mm. Mounted on imaging room wall 1 metre from subject with its inferior border 1 metre from the ground. This was mounted with 16 Scotch mounting squares 25 x 25 mm. By requesting subjects to look into their own eyes, this is used to provide a visually guided registration of NHP.

d) **Plumb Line** – The 2 metre long plumb line was a heavy duty waxed cotton fishing line (dark green) donated by “Totally Hooked” fishing store, 250 Pirie Street, Adelaide. This line was weighted with a 500 gram plumb weight (Figure 21) fixed to the wall with permanent nail attachment. This provides a true vertical line in each lateral head photo, which was later transferred to the lateral cephalograph. A 20 mm unit scale was placed adjacent to this.

Figure 21. Plumb weight keeping the plumb line vertical

e) **Foot Marks** – Cut out of adhesive book cover. Placed at 1 metre away from mirror on the wall to aid the photographer guiding the subject into the appropriate position.

f) **Fluid Level** – This was used to calibrate the lens of the camera to a true horizontal angulation (Figure 22). It was felt that both sides of the lens were parallel to each other. The lens therefore, was cylindrical, not conical in shape.

Figure 22. Fluid level used to calibrate camera lens to true horizontal

7.5.2 Photographic Rig

The photographic rig for recording NHP was set up in the imaging room of the Orthodontic Department, 4th Floor, Adelaide Dental Hospital, Australia. A vertical plumb line was fixed to the wall 0.90 metres from the wall mounted mirror. This allowed the subjects to stand approximately 1 metre from the wall mounted mirror and therefore effectively look a distance of 2 metres into their eyes (Figure 23). This distance was felt to be sufficiently long enough to allow subjects to posture into a visually guided NHP suggested by other investigators [7, 17, 32, 35, 40, 42, 48, 91, 92].

The centroid of each adhesive foot mark were placed 1 metre from the wall mounted mirror as a guide for the photographer to position the patient accurately and consistently.

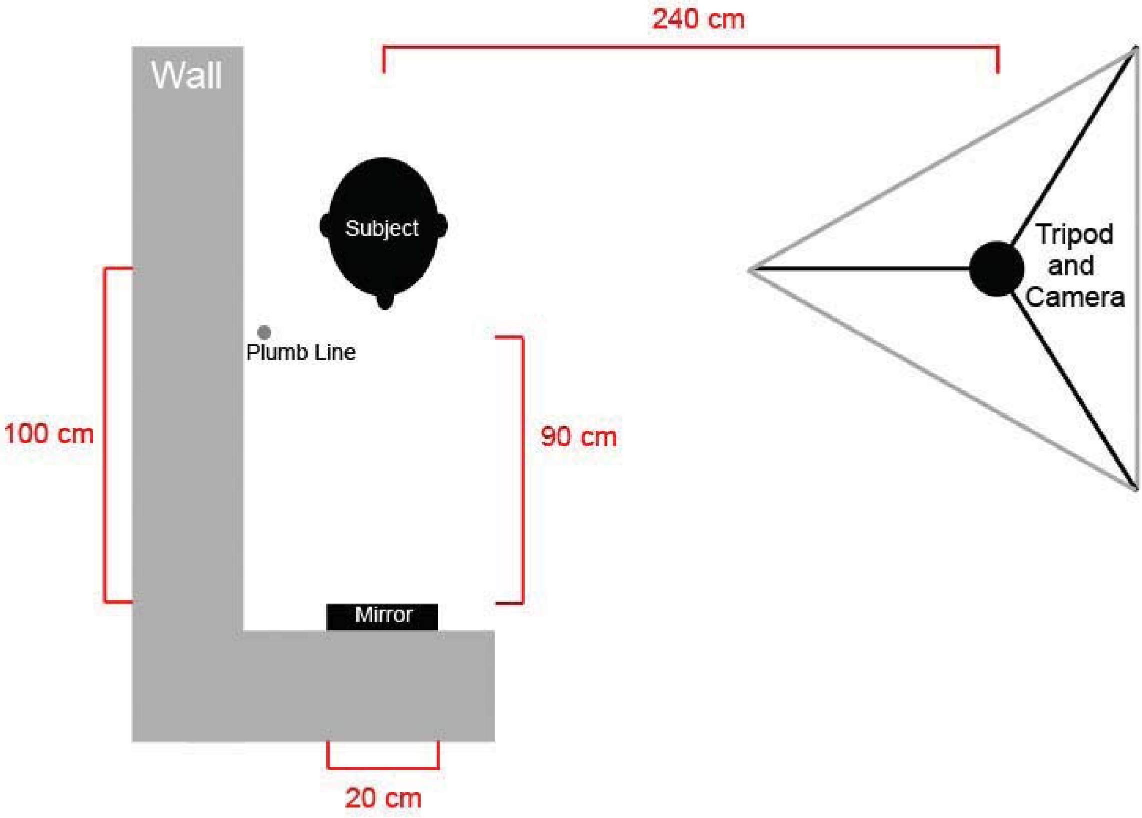


Figure 23. Floor plan of photographic rig

7.5.3 Pilot Test of Rig

A pilot test was carried out by placing a large grid and plumbline in the field of photographic view to determine any distortions that may affect the interpretation of results. The resultant image showed consistently even grid units across the entirety of the image, validating the lens and camera set up.

7.6 Photographic Protocol

The photographic technique involved establishing the subjects in NHP in preparation for image exposures at T1 and T2. This preparation closely followed the protocol outlined by Solow and Tallgren [7]. Subjects were standing and initially asked to assume their arms by their sides to establish orthoposition [79]. Then they were instructed to close their eyes. After a series of neck bending exercises with decreasing amplitude, subjects reopened their eyes and looked into their eyes on the wall mounted mirror, and were asked to walk forward about 2 metres slowly until the photographer guided them to the 1 metre mark. At no stage were the subjects allowed to lose visual contact with their own eyes during this walk. This placed the subject’s eyes 1 metre away from the wall mounted mirror. Subjects were then asked to stay still, with teeth together and lips relaxed. A lateral head photograph was then taken.

All lateral head photographs were taken with the Canon 300D SLR digital camera as illustrated in Section 7.5.1. b). The camera settings were as follows,

• Shutter speed value	1/60 seconds
• Aperture value	f/14
• ISO speed rating	100
• Exposure bias value	0.00 EV
• Pixel dimensions	2048x3072 pixels
• Exposure mode	manual
• White balance mode	manual (Flash)
• Flash Bias Value	+1.67 EV

7.6.1 Photographic Image Processing

All lateral head photographs were edited for contrast and brightness in Adobe Photoshop CS (Adobe systems Inc., San Jose, USA). The background was set to white, and the true vertical plumb line was oriented with vertical to rotate the images (Figure 24).

7.7 Tracing the Lateral Head Radiograph

7.7.1 Landmark verification

To aid in lateral cephalometric landmark identification, a process of landmark verification was performed. Some of the lateral cephalometric landmarks that were used for the analysis were identified on a dry skull. Metallic markers were placed on these points with radiolucent modelling clay. A lateral head radiograph was taken and the radio-opaque points produced by the metallic markers (Figure 25) were visually compared to their positions on the dry skull. The landmarks identified are summarised in Table 3.

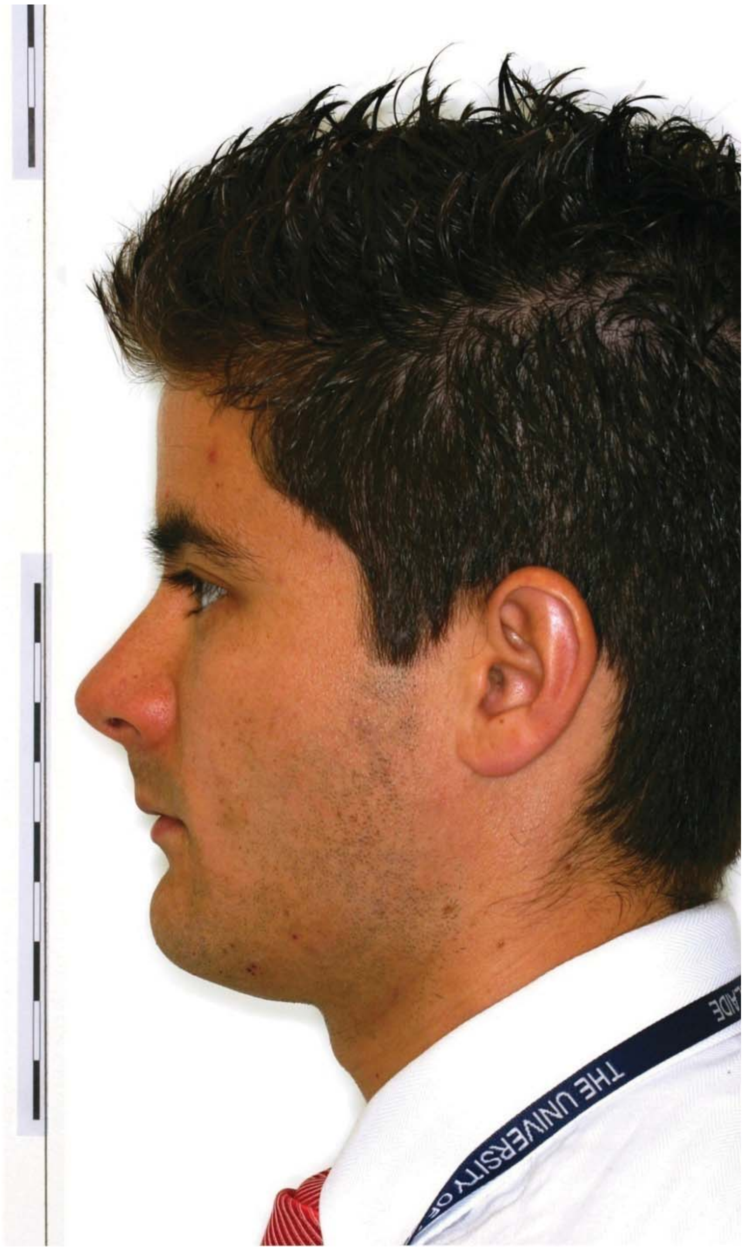


Figure 24. Processed image from the photographic recording of natural head position

Table 3. Landmark verification metallic markers

Number	Landmark Name	Abbreviation
1	Anterior nasal spine	ANS
2	Basion	Ba
3	Inferior border of optic canal	OCinf
4	Nasion	N
5	Opisthion	Op
6	Orbitale	Or
7	Porion	Po
8	Posterior Nasal Spine	PNS
9	Pterygomaxillare	Ptm
10	Pterygomaxillary fissure, inferior	PTM
11	Superior orbital margin	SOr

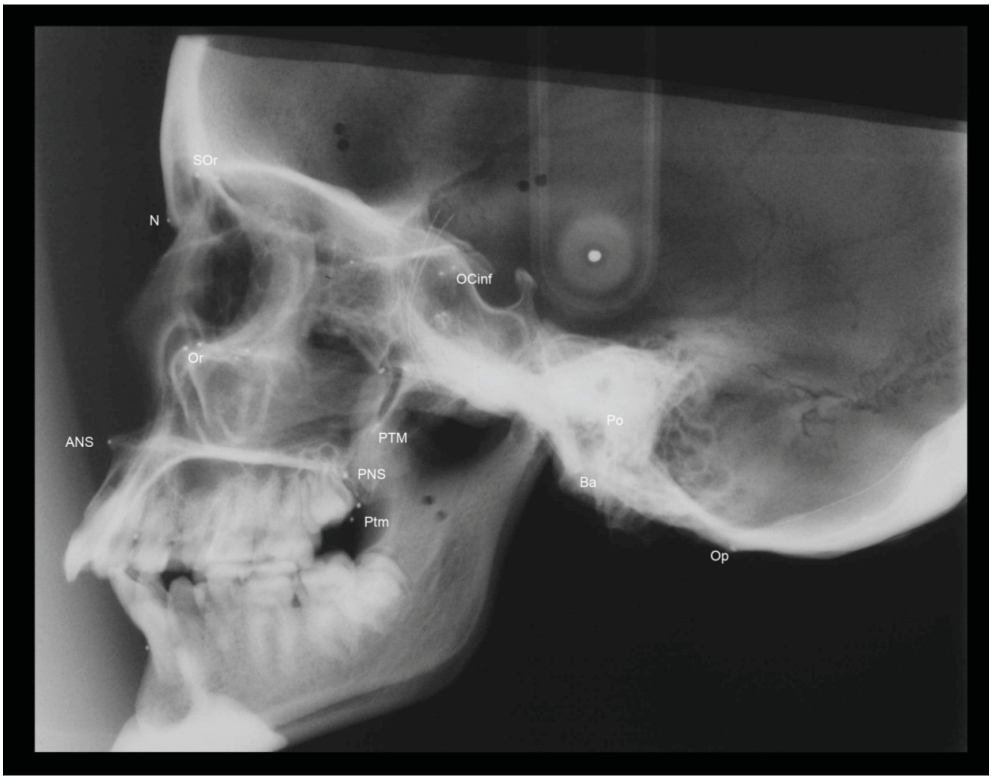


Figure 25. Lateral head radiograph of dry skull with metallic markers placed on landmarks of interest

7.7.2 Tracing Technique

The tracings were all performed in a standardised, suitably darkened room on a light box. Opaque black cardboards were used to restrict the field of vision to the particular areas of interest [93]. To maintain consistency and minimise method error, a single operator was used for the tracing and landmark identification.

The tracing technique involved attaching the cephalometric radiograph facing to the left of the viewing screen with adhesive tape. Matte acetate orthodontic tracing paper (3M Unitek Cephalometric Tracing Acetate) was placed over the cephalometric radiograph using adhesive tape and a single 0.5mm HB mechanical pencil was used for all tracings to ensure consistency. The patient identification number and date of the lateral head radiograph were placed at the bottom of each tracing.

To establish linear measurement comparison between each tracing, the radiographic calibration ruler was traced as well. For the 48 subjects taken with phosphor plate films (Section 7.4), the full 45 mm calibration ruler was not completely visible on the landscape lateral head film. For these subjects, a full 45 mm calibration ruler was traced from a portrait film with the same magnification.

The cephalometric tracings were then scanned to create an electronic duplicate. This was done using an Epson flatbed film scanner, Epson Perfection 4990 PHOTO and Pentium 4, 2.8GHz desktop computer. The scan settings were as follows,

• Resolution	300 dots per inch
• Colour Depth	16 bit greyscale
• Program	Epson Scan Version 2.61

7.8 Transfer of True Vertical Plane

Transfer of the true vertical plumb line in the lateral head photographs to its corresponding lateral head radiograph tracing was done using a computerised manual superimposition technique. The computer hardware used was a Windows XP based PC with Intel Centrino 1.8 GHz, 512Mb RAM, 80Gb hard drive. This transfer was achieved using the program Adobe Photoshop CS (Adobe systems Inc., San Jose, USA) in the following steps.

7.8.1 Step 1

Both the lateral head photograph and scanned tracing were opened in Adobe Photoshop CS as separate windows. The plumb line in the lateral head photograph was copied, placed in a new layer, and moved in a parallel fashion closer to the subject's profile (Figure 26).

NOTE: This figure is included on page 65 of the print copy of the thesis held in the University of Adelaide Library.

Figure 26. Manually moving the plumb line in a parallel fashion

7.8.2 Step 2

The tracing was then copied from its window and pasted into the lateral head photograph window into a new layer. The tracing layer was set to 50% opacity. This was then rotated and resized without changing its proportions, and finally superimposed on the photograph across the nose and forehead profiles (Figure 27). These structures were felt to be the least changing compared with those of the lips and chin which are affected by muscle posture.

NOTE: This figure is included on page 66 of the print copy of the thesis held in the University of Adelaide Library.

Figure 27. Tracing superimposed on photograph using forehead and nose

7.8.3 Step 3

Finally, with the superimposition complete, the tracing layer was returned to 100% opacity, and a white layer placed on top of the original photograph layer (Figure 28). This produced a lateral head cephalometric tracing with the correct orientation to the true vertical plumb line. This “VER transfer” file was saved as a Photoshop (.psd) file and JPEG (.jpeg) file for compatibility with other software. The .jpeg file was then digitised for measurement.

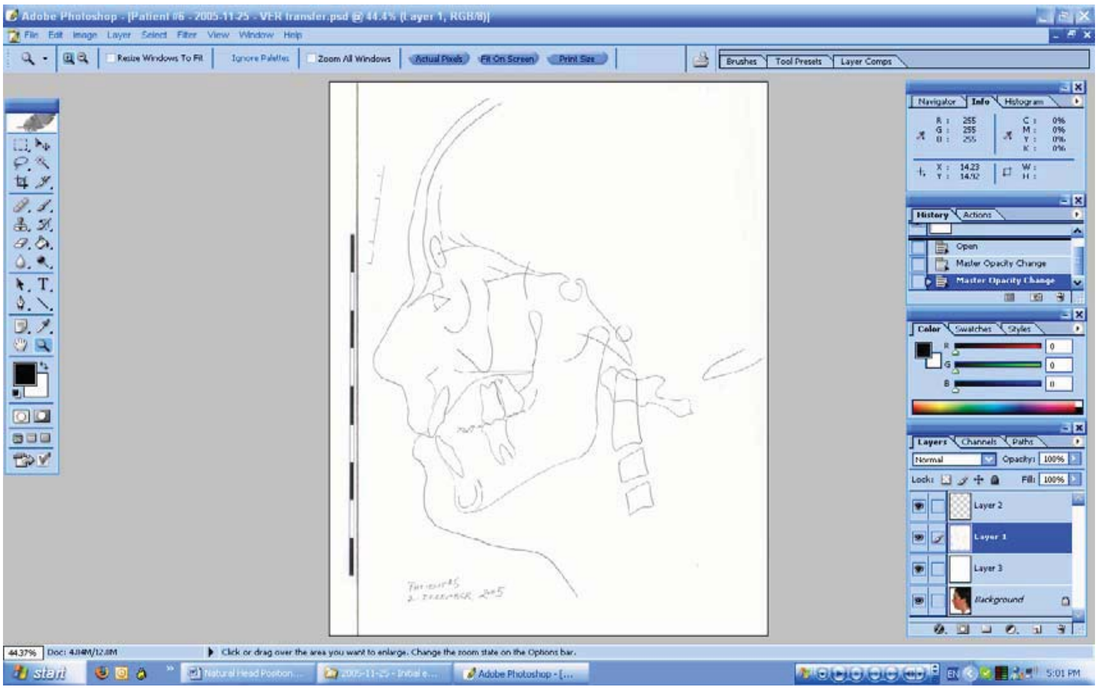


Figure 28. Final cephalometric tracing with true vertical plumb line transferred

7.9 Cephalometric Analysis

7.9.1 Digitising Technique

All the tracings were digitised on the Mona Lisa Craniofacial Planner (Tidbinbilla Pty Ltd, Canberra, Australia) software package for Windows. A custom analysis was developed in this program to measure the specific variables for the present study. The hardware used for this stage was a Microsoft Windows based Pentium 4 2.8GHz, 512MB RAM, 40GB HD personal computer.

The following digitisation protocol was used:

1. The VER transfer file (saved as .jpeg) was imported into software package
2. The patient identification number and date of photograph recorded
3. All the landmarks were digitised, allowing the software to calculate all angular and linear variables.
4. This procedure was repeated for each VER transfer file (photographic registration of NHP)

The data were then saved for each VER transfer file in a format (.csv) that could be imported to Microsoft Excel 2003 (Microsoft Inc.). These data were then opened in Microsoft Excel 2003 spreadsheets for data organisation and calculations. The statistical software package SPSS (Apache software foundation) was also used for graphical interpretation of the data.

7.9.2 Cephalometric Landmarks

All landmarks for each tracing were identified in the same sitting. The landmarks used were similar to those in Barbera's [94] previous work (Figure 29). These landmarks are defined in Appendix 11.2.1 and outlined in the Table 4 below.

Table 4. Cephalometric landmarks and abbreviations used

Number	Landmark Name	Abbreviation
1	Anterior nasal spine	ANS
2	Anterior tubercle	At
3	Articulare	Ar
4	Basion	Ba
5	Apex of 2nd cervical vertebra	cv2ap
6	Ethmoid registration point	SE
7	Gonion	Go
8	Maxillon	Max
9	Menton	Me
10	Nasion	N
11	Occipitale	Occ
12	Opisthion	Op
13	Orbital margin point	OM
14	Orbitale	Or
15	PM point	PM
16	Porion	Po
17	Posterior Nasal Spine	PNS
18	Posterior tubercle	Pt
19	Pterygomaxillare	Ptm
20	Pterygomaxillary fissure, inferior	PTM
21	Sella	S
22	Sella tangent	St
23	Superior orbital margin	SOr
24	Tuberculum sella inferior	Ti

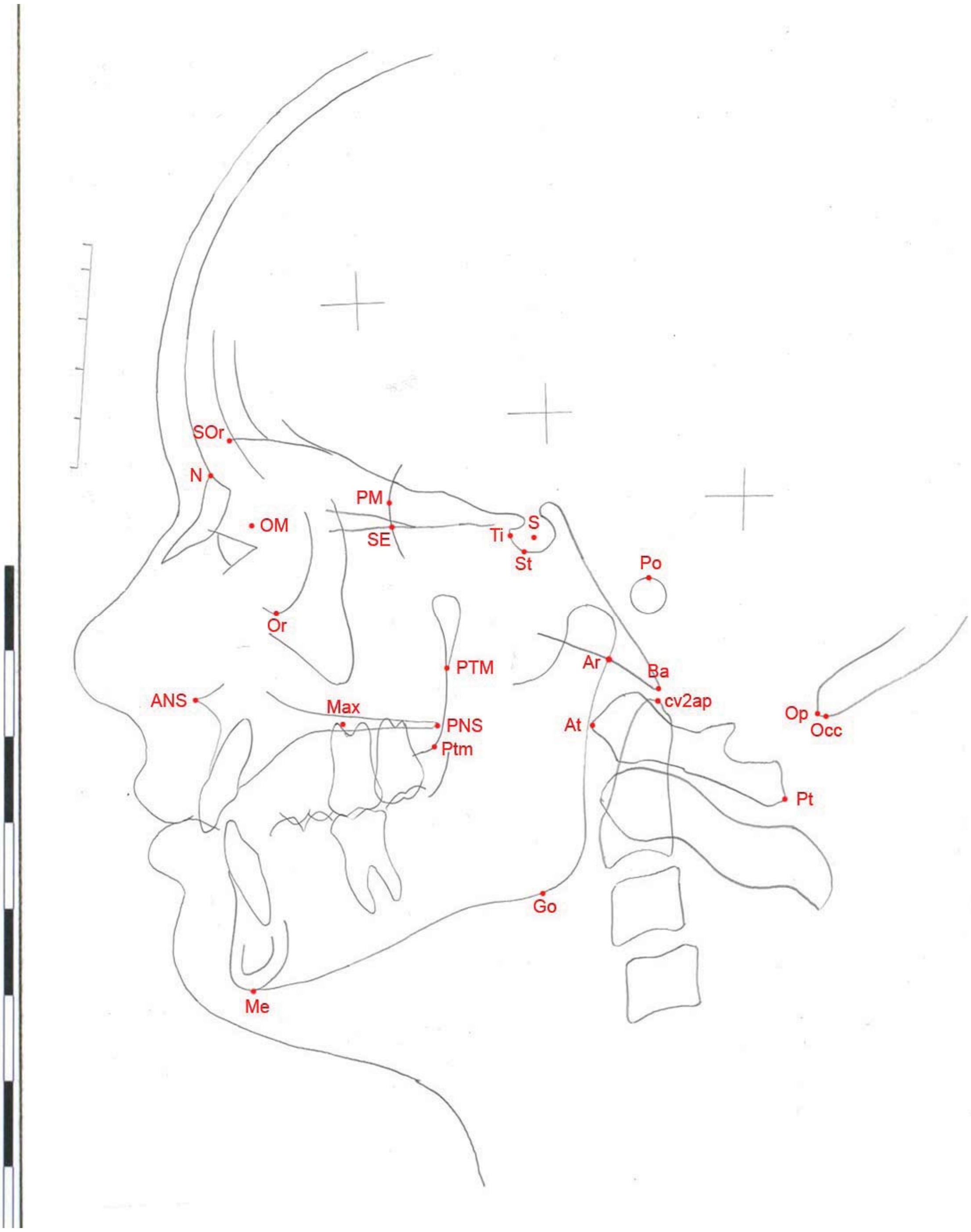


Figure 29. Cephalometric landmarks identified for plane construction

7.9.3 Cephalometric Planes

The cephalometric planes chosen for analysis in the present study were selected to represent all areas of the skull and, therefore, not limit or bias the results. These planes were constructed from the definitions in Appendix 11.2.2 using the landmarks outlined in Section 7.9.2. These are listed below in Table 5 and illustrated in Figure 30.

Table 5. Cephalometric planes and abbreviations used

Plane	Description	Construction	Abbreviation
1	Anterior-posterior tubercle of C2	At-Pt	AtPt
2	Foramen magnum line	Ba-Op	FML
3	Frankfort Horizontal	Po-Or	FH
4	Functional occlusal plane	Best fit	FOP
5	Krogman-Walker line	Occ–Max	KW line
6	Mandibular plane	Me-Go	Md plane
7	Neutral horizontal axis	OM-Ti	NHA
8	Palatal plane	ANS-PNS	P plane
9	Posterior maxillary plane	PM-Ptm	PM plane
10	Posterior nasomaxillary vertical	SE-PTM	PM vertical
11	Sella nasion	S-N	SN
12	Sella tangent nasion	St-N	StN
13	True horizontal line	90° to plumb line	HOR

7.9.4 Angular Variables Measured

The cephalometric analysis used by Barbera [17, 94] was adapted to compare angular variables to true horizontal (HOR) for variability. Additionally, some planes were compared with each other by angular measurements. The mean, standard deviation (SD), range (min, max), coefficient of variation (CV) and Student's *t*-test were determined for each variable by sex and pooled samples (Appendix 11.3.3). The angular variables measured are outlined in Table 6.

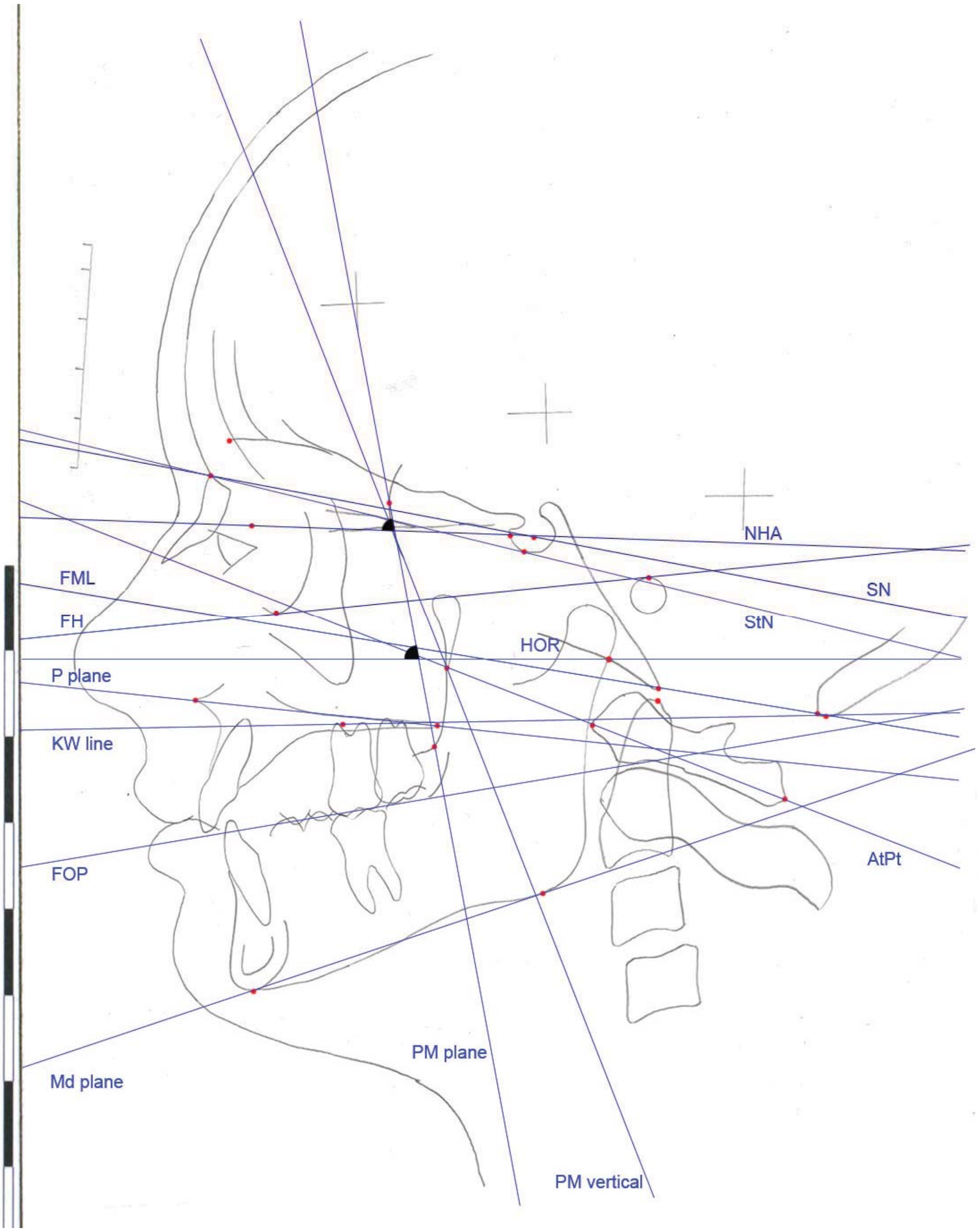


Figure 30. Cephalometric planes constructed to measure angular variables

Table 6. Description of angular variables measured

Angle	Description of angular variable	Abbreviation
1	True horizontal to Frankfurt Horizontal	HOR/FH
2	True horizontal to sella-nasion	HOR/SN
3	True horizontal to sella tangent-Nasion	HOR/StN
4	True horizontal to Neutral horizontal axis	HOR/NHA
5	True horizontal to Krogman-Walker line	HOR/KW line
6	True horizontal to Palatal plane	HOR/P plane
7	True horizontal to Foramen magnum line	HOR/FML
8	True horizontal to ant. tubercle-post. tubercle	HOR/AtPt
9	True horizontal to Functional occlusal plane	HOR/FOP
10	True horizontal to Mandibular plane	HOR/Md plane
11	True horizontal to Posterior maxillary plane	HOR/PM plane
12	Foramen magnum line to ant. tubercle-post. tubercle	FML/AtPt
13	Krogman-Walker line to Mandibular plane	KW line/Md plane
14	Neutral horizontal axis to Posterior maxillary plane	NHA/PM plane
15	Posterior maxillary plane to Posterior nasiomaxillary vertical	PM plane/PM vert

All angles were defined as the minimum angular rotation from the first plane to the second. With the patient facing left, a clockwise rotation was assigned a positive value and an anticlockwise rotation a negative value. The exception to this rule was NHA/PM plane and HOR/PM plane which was defined as the angular magnitude of clockwise rotation from the first plane to the second – when the patient is facing left (Figure 30).

7.9.5 Linear Variables Measured

The four linear measurements were measured as per the work of Barbera [17, 94]. These variables are outlined in Table 7 and Figure 31 using the cephalometric landmarks identified in Section 7.9.2. The mean, standard deviation (SD), range (min, max) coefficient of variation (CV) and Student's *t*-test was calculated for each variable by sex and pooled samples.

Table 7. Linear variables measured

Variable	Description of Linear variable	Abbreviation
1	Basion to 2nd cervical vertebral apex	Ba-cv2ap
2	Basion to Krogman Walker line perpendicular	Ba-KW line
3	Basion to Opisthion	Ba-Op
4	Ant. tubercle to Post. tubercle of 2nd cervical vertebra	At-Pt

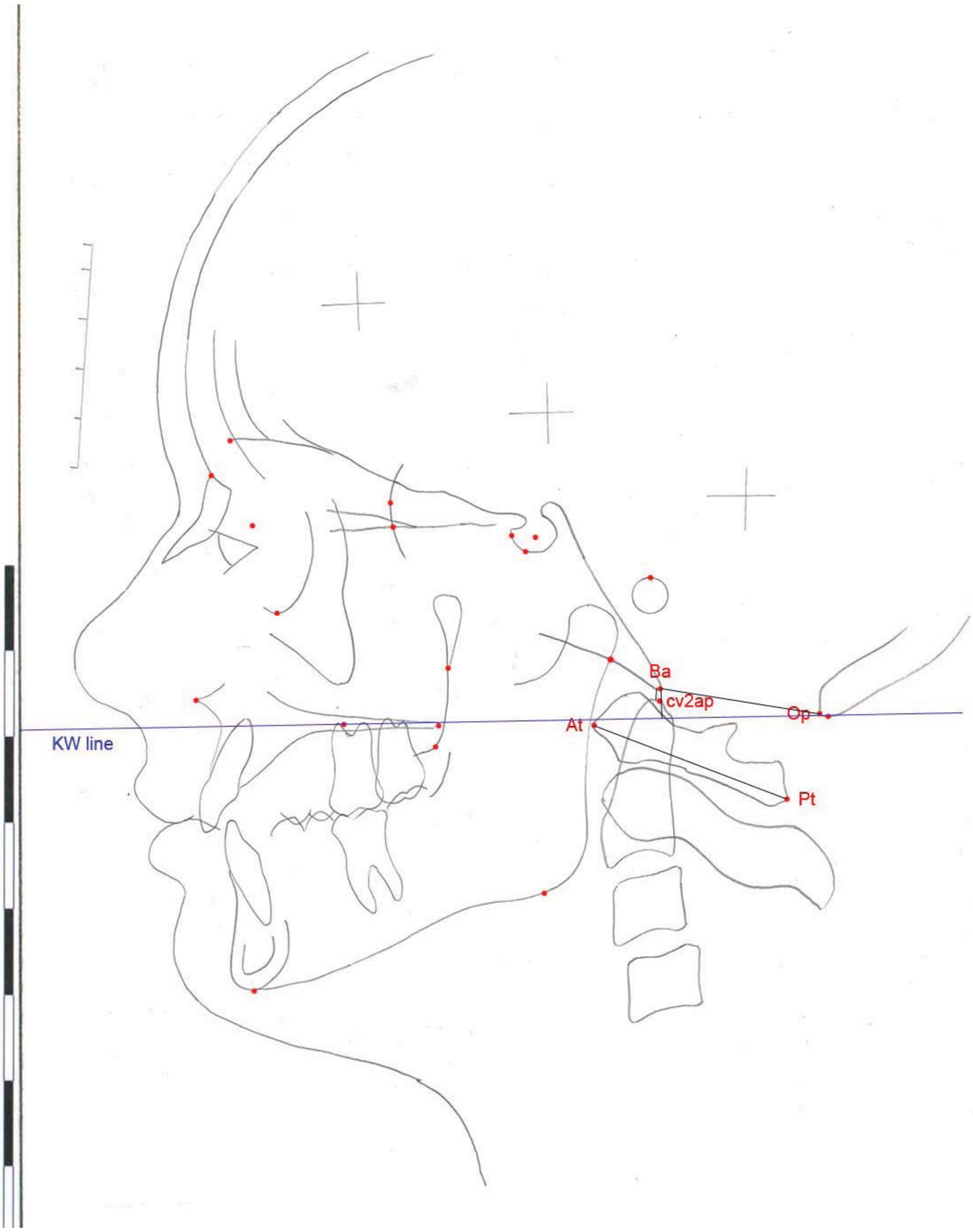


Figure 31. Linear variables measured

7.10 Reproducibility of Natural Head Position

A second photographic registration of NHP was taken at T2 (average 1.98 months after T1). This was performed using the same photographic protocol as T1 outlined in Section 7.6. This T2 lateral head photograph was then superimposed with the original lateral head radiograph tracing (Section 7.8). Therefore the same cephalometric tracing was oriented to the true vertical line at T2 and T1 to determine NHP reproducibility.

The angular variable, HOR/SN, was compared at T1 and T2 because SN was thought not to change in this time period. An extension of the head between T1 and T2 was defined as a positive rotation and the opposite as a negative rotation. Any difference in this angle will give an indication of how the head position varied between T1 and T2. This will effectively indicate the reproducibility of NHP in the present study.

The data were tested for normality, then the mean difference (Mean diff), standard deviation of the difference (SD diff), paired Student's *t*-test and Dahlberg statistic, S(i) were calculated for the HOR/SN variable.

7.11 Method Error

7.11.1 Cephalometric Software Validation

The Mona Lisa Craniofacial Planner software package was tested for accuracy and reliability. This was done using a mathematically generated grid containing equal squares and creating three lines to test. The variables tested were as follows(Figure 32),

1. an intersection angle between two visible lines (AC/BE)
2. an intersection angle between two lines that do not visibly cross (AC/DF)
3. a linear measurement (A-E)

The variables were calculated using simple trigonometry outlined in Appendix 11.3.2. The variables were then measured using Mona Lisa Craniofacial Planner and compared to the calculated values. This process was repeated 10 times and the mean, standard deviation and range were calculated to test reliability.

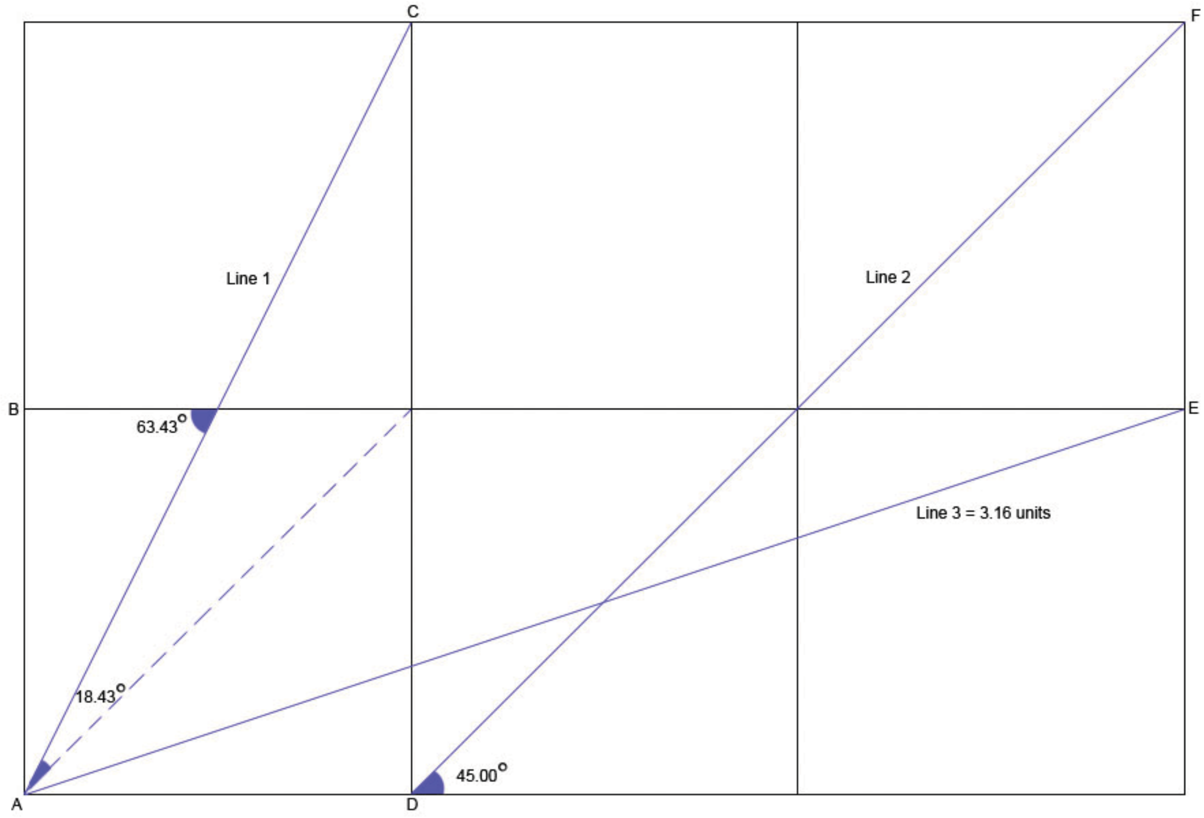


Figure 32. Grid and constructed lines to validate use of software

7.11.2 Error of Overall Method

To determine error of the overall method, 20 patients were selected at random by means of subject identification numbers drawn out of a hat by a colleague. The cephalometric radiographs of these patients were re-traced, tracings re-scanned and re-processed with correct orientation to the true vertical line. These were then digitised for comparison with the first determinations. This was performed at least 1 month after the original tracing process.

Systematic errors were determined by calculating the mean difference (Mean diff), standard deviation of the difference (SD diff), paired Student’s *t*-test (*t*-test), and *p* value (Appendix 11.3.4). Random errors were determined by calculating the standard error of a single observation or Dahlberg value, S(i), error variance, E(var), reliability (Appendix 11.3.4).

7.11.3 Error of Vertical Plumbline Transfer

The vertical plumbline transfer process from the lateral head photograph to the lateral head radiograph tracing was one step in the overall method. The method error of this step only was determined. Using the same set of 20 subjects, each subject's tracing was re-superimposed over its respective photograph at least 1 month after the first determination, and the true vertical re-transferred to each tracing as per the method outlined in Section 7.8.

The mean difference (Mean diff), standard deviation of the difference (SD diff), paired *t*-test, Dahlberg value, S(i) were calculated for one variable, HOR/Ref plane angle (Appendix 11.3.4). This arbitrary reference plane was constructed from two points on each tracing - the posterior most locating cross to the inferior most aspect of the tracing scale ruler (Figure 33).

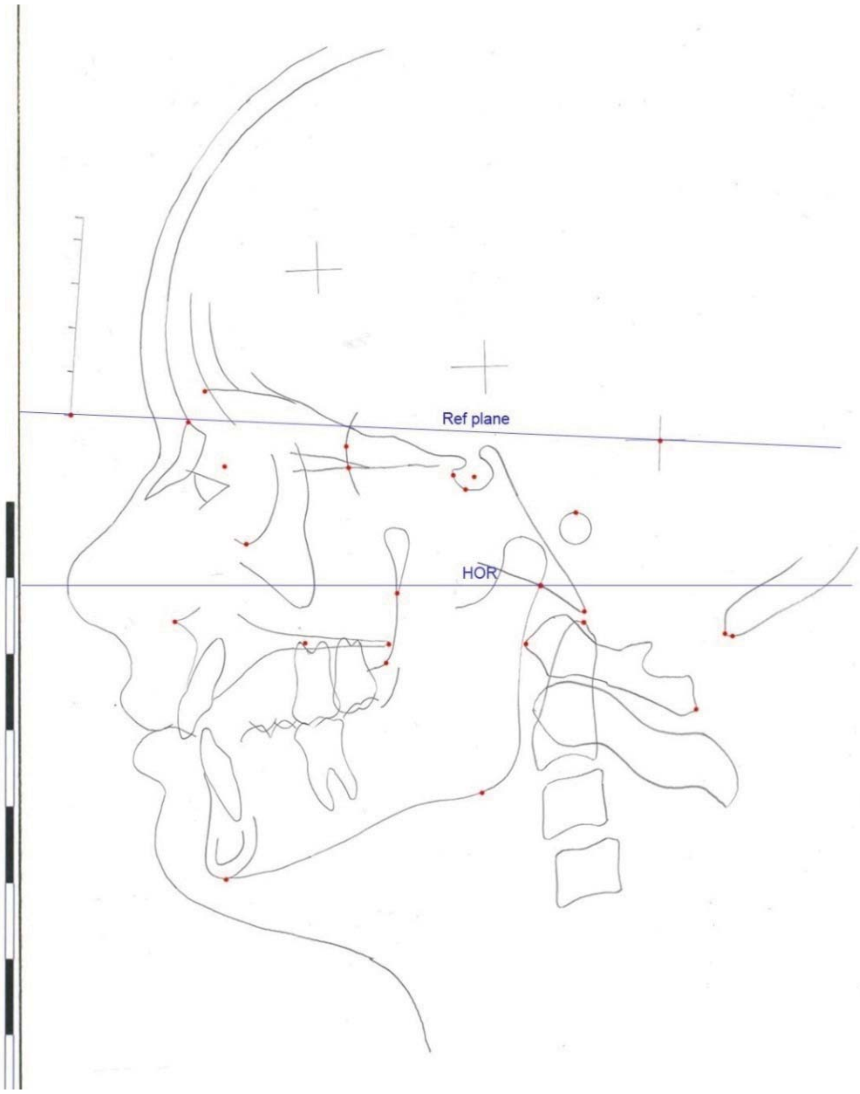


Figure 33. Method error determination for transfer of VER plane

8. Results

8.1 Power Test

The power of a statistical analysis is the ability to show a difference when there is a true difference (i.e. reject the null hypothesis). A statistical power test calculates the probability of not committing a type II statistical error (β) at a chosen level of type 1 (α) error. This test was used to confirm the sample size in the present study to be of adequate size for reasonable statistical analysis.

8.1.1 Variability of Craniofacial Reference Planes

The total pooled sample size of the present study was n=57 subjects after the applied exclusion criteria. The standard deviation σ=5.3° was taken from previous investigators [15] and the difference of means as μ_1-μ_2=2°, a clinically acceptable value.

When α=0.05, the power for this sample size was 82% as per the calculations in Appendix 11.3.1. An α of 0.05 and β of 0.18 are deemed acceptable levels for reasonable statistical analysis in the present study.

8.1.2 Reproducibility of Natural Head Position

The sample size of those subjects recorded in NHP at both T1 and T2 was n=39. The standard deviation of reproducibility was taken from Cooke's data [12], σ=3° and the difference of means as μ_1-μ_2=2°, a clinically acceptable value.

The power for this sample size was 99% as per the calculations in Appendix 11.3.1. There is very little chance of committing a type II error here.

8.2 Method Error

Three method error tests were carried out to assess the degree of error attributed to the method of producing data in the present study.

8.2.1 Cephalometric Software Validation

This validation was carried out prior to any measurements to confirm that the Mona Lisa Craniofacial Planner software package was of suitable accuracy and reliability for the present study (Section 7.11.1).

Calculated values for the angular and linear measurements were determined using right angled triangle trigonometry (Appendix 11.3.2). These calculated values are compared with the measured values in the software package (Table 8). All three variables tested showed very little difference between the software measured and trigonometry calculated values. Therefore, the software was deemed to be of acceptable accuracy and reliability (low SD) for use in the present study.

Table 8. Accuracy and reliability of cephalometric software

		Measured Values (repeated 10 times)			
Variable	**Actual Value**	**Mean**	**SD**	**Min**	**Max**
AC-BE(°)	63.43	63.39	0.06	63.31	63.54
AC-DF (°)	18.43	18.38	0.03	18.31	18.43
AE (units)	3.16	3.16	0.00	3.16	3.17

8.2.2 Error of Overall Method

The basis of the error study consisted of double determination of variables through repetition of the entire tracing, transfer of VER, landmark identification, and digitisation process using a sample of 20 subjects chosen randomly (Section 7.11.2). The working level of significance was set at $p<0.05$ for all statistical tests.

Each variable was tested for systematic (paired *t*-tests) and random errors (Dahlberg values) as shown in Table 9.

Table 9. Method error: Results for double determinations for tracing, scanning, VER transfer and digitisation process (N=20)

		Systematic error				**Random Error**		
Angular Variables (°)	**N**	**Mean diff**	**SD diff**	***t*-test**	***p* value**	**S(i)**	**E(var)**	**Reliability**
HOR/FH	20	-0.04	0.90	0.18	0.86	0.62	1.79	98.21
HOR/SN	20	0.11	0.88	0.55	0.59	0.61	1.41	98.59
HOR/StN	20	-0.18	0.82	1.00	0.33	0.58	1.28	98.72
HOR/NHA	20	0.31	1.43	0.97	0.34	1.01	3.54	96.46
HOR/KW line	20	-0.44	0.57	**3.23**	**0.00**	0.50	1.14	98.86
HOR/P plane	20	-0.80	1.21	**2.80**	**0.01**	1.01	3.99	96.01
HOR/FML	20	-0.57	1.26	1.96	0.06	0.96	2.21	97.79
HOR/AtPt	20	-0.06	0.70	0.36	0.72	0.48	0.40	99.60
HOR/FOP	20	0.82	1.65	**2.14**	**0.04**	1.28	5.86	94.14
HOR/Md plane	20	-0.16	0.69	1.04	0.30	0.49	0.51	99.49
HOR/PM plane	20	-0.47	1.01	2.02	0.05	0.77	2.70	97.30
FML/AtPt	20	0.35	1.59	**2.38**	**0.02**	1.12	3.61	96.39
KW line/Md plane	20	0.28	0.61	1.15	0.26	0.47	0.78	99.22
NHA/PM plane	20	-0.78	1.12	0.96	0.34	0.95	4.67	95.33
PM plane/PM vert	20	-0.14	1.04	1.96	0.06	0.72	9.13	90.87
Linear Variables (mm)	**N**	**Mean diff**	**SD diff**	***t*-test**	***p* value**	**S(i)**	**E(var)**	**Reliability**
Ba-cv2ap	20	0.30	0.81	1.59	0.12	0.60	12.32	**87.68**
Ba-KW line	20	0.01	0.81	0.08	0.94	0.56	6.01	93.99
Ba-Op	20	-0.59	1.19	**2.15**	**0.04**	0.92	8.08	91.92
At-Pt	20	0.28	0.52	**2.30**	**0.03**	0.41	1.21	98.79

Significant values of t>2.09 & $p<0.05$ level are in bold, Reliability values <90% are in bold

The critical t value for N=20 (df=19) and $p=0.05$ was 2.093. The variables that showed significant systematic error ($t>2.093$) were HOR/KW line, HOR/P plane, HOR/FOP, NHA/PM plane, Ba-Op and At-Pt. Reliability was greater than 90% for all variables except Ba-cv2ap which had a reliability of 87.7 %.

From these results, it would seem that error in the overall method will not bias the results of the present study. However, any interpretation of the following variables should account for some systematic error,

- HOR/KW line
- HOR/P plane
- HOR/FOP
- FML/AtPt
- Ba-Op
- At-Pt

8.2.3 Error of Vertical Plumbline Transfer

From the same set of double determinations in Section 7.11.3 (N=20), the true horizontal to reference plane angle, HOR/Ref, mean difference (Mean diff) and standard deviation of the difference (SD diff) were calculated. This variable was also tested for systematic (paired *t*-test) and random errors (Dahlberg value). The working level of significance was set at $p<0.05$.

Table 10. Descriptive statistics of vertical plumbline transfer method error (N=20)

Angular variable (°)	N	Mean diff	SD diff	*t*-test	*p* value	S(i)
HOR/Ref	20	0.16	0.60	1.15	0.26	0.43

The results (Table 10) illustrate no significant difference between determinations for plumbline transfer. The standard deviation of the difference and Dahlberg values are sufficiently low to suggest this method of vertical plumbline transfer has an acceptable level of error for use in the photographic method outlined in Section 7.8.

8.3 Sample Size, Age & Observation Times

A total of 67 subjects consented and were recorded photographically in natural head position at T1. 10 subjects were excluded from the present study for the following reasons,

- Cephalometric film size too small causing cropping of required radiographic anatomy (8 subjects)
- Subject didn't meet age requirements (2 subjects)

Therefore a total of 57 subjects were included in the present study for data analysis at T1. At T2, a total of 39 subjects were followed up for photographic NHP registration to assess reproducibility of the present study.

The distribution of ages at T1 and T2 are shown by sex and pooled samples below (Tables 11 and 12).

Table 11. Age of subjects at T1 (years)

	Total N=57				Female N=38				Male N=19			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
T1	15.4	1.5	11.8	18.3	15.6	1.4	13.3	18.3	15.1	1.5	11.8	17.7

Table 12. Age of subjects at T2 (years)

	Total N=39				Female N=25				Male N=14			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
T2	15.4	1.5	11.9	17.8	15.6	1.5	13.5	17.8	15.2	1.7	11.9	17.8

At the initial examination (T1), the lateral head photograph was taken on the same day as the lateral cephalograph where possible (Table 13). When this wasn't possible, the photo was usually taken shortly after the radiograph (0.1 months). There was little variation in this time period (SD 0.3 months).

Thirty nine patients were then followed up 2 months later at T2. The mean period between the lateral cephalograph and T2 was 2.1 months, ranging from 0.9 to 6.1 months (Table 14). This was felt to be short enough to minimise the effects of growth at the nose and forehead for the VER transfer process. The mean time period of 2.0 months between T1 and T2 was felt to be sufficiently long enough to test the reproducibility of natural head position with minimal patient bias (Table 15).

Table 13. Time period between lateral head radiograph and T1 photograph (months)

	Total N=57				Female N=38				Male N=19			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Ceph-T1	0.1	0.3	-0.2	1.2	0.1	0.3	-0.2	1.2	0.0	0.2	0.0	0.7

Table 14. Time period between lateral head radiograph and T2 photograph (months)

	Total N=39				Female N=25				Male N=14			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Ceph-T2	2.1	1.1	0.9	6.1	2.1	1.0	0.9	4.9	1.9	1.3	1.2	6.1

Table 15. Time period between first and second lateral head photographs (months)

	Total N=39				Female N=25				Male N=14			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
T1-T2	2.0	1.1	0.9	6.1	2.1	1.0	0.9	4.9	1.9	1.3	1.2	6.1

8.4 Cephalometric Analysis

All data were first tested for normality. This was performed using two visual methods involving box plots (Figure 34 & Figure 35) and histogram distributions of data for each variable. For all variables, the data appeared to be distributed about the median with an acceptable level of normality. Estimates of skewness and kurtosis showed no clear trends of a significant lack of normality in data distribution for the 19 variables. The variables could, therefore, be accepted as being normally distributed and described adequately in terms of means and standard deviations.

The results of the statistical analyses are presented in tabular form. The linear measurements are all calculated in millimetres (mm) and the angular measurements are all calculated in degrees (°).

8.4.1 Descriptive Statistics

Descriptive statistics are outlined below for all angular and linear variables by females (N=38) and males (N=19) at T1.

The mean, standard deviation (SD), range (Min, Max), and coefficient of variation (CV) were calculated for all variables outlined in Table 6 and 7. Only positive coefficients of variation are shown. Descriptive statistics were initially determined by sex for females (Table 16) and males (Table 17).

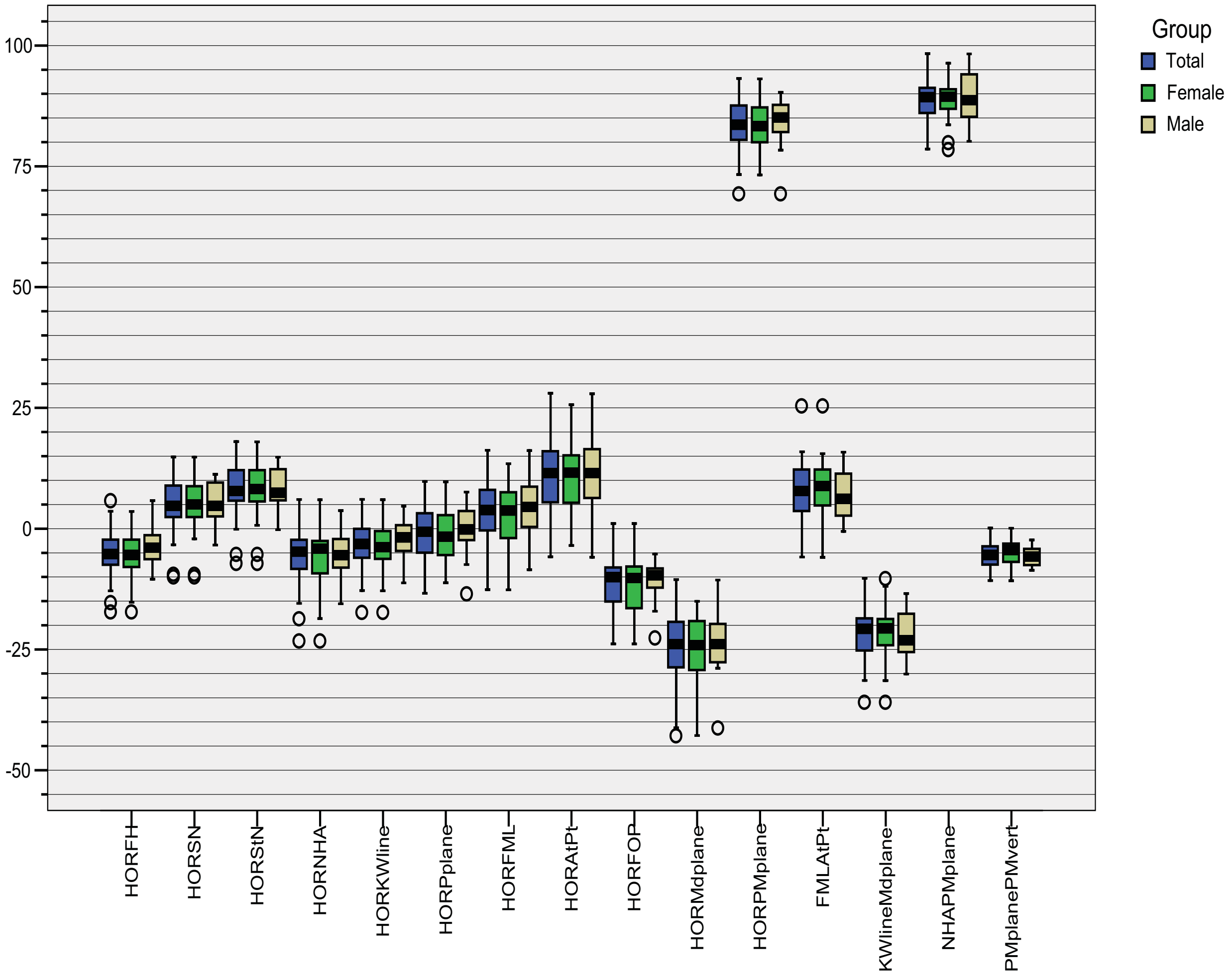
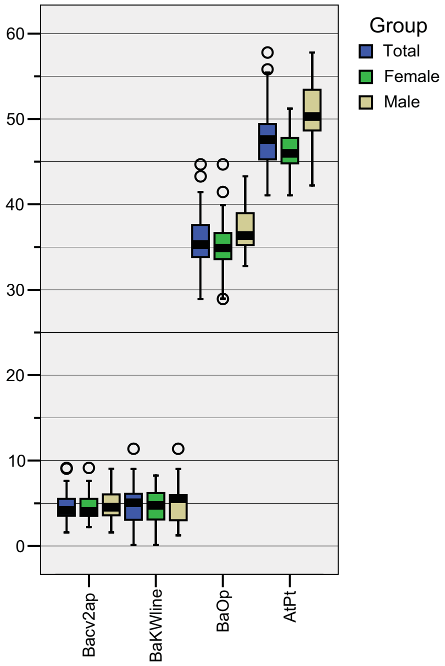


Figure 34. Box plot distribution of angular variable data (°)



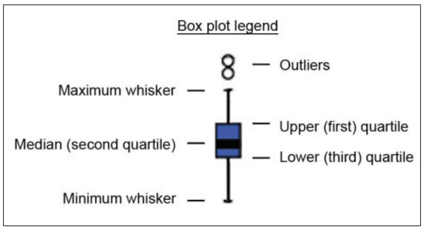


Figure 35. Box plot distribution of linear variable data (mm)

Table 16. Descriptive statistics for females (N=38) for all angular and linear variables at T1

Angular Variables(°)	Mean	SD	Min	Max	CV
HOR/FH	-5.40	4.88	-17.12	3.60	
HOR/SN	5.34	5.46	-9.88	14.86	102.15
HOR/StN	8.38	5.44	-7.05	18.02	64.90
HOR/NHA	-5.47	5.75	-23.13	6.04	
HOR/KW line	-3.58	4.94	-17.22	6.08	
HOR/P plane	-1.44	5.04	-11.13	9.77	
HOR/FML	2.90	6.41	-12.58	13.53	220.68
HOR/AtPt	11.06	7.37	-3.46	25.72	66.66
HOR/FOP	-11.53	5.71	-23.82	1.11	
HOR/Md plane	-25.02	6.96	-42.77	-15.01	
HOR/PM plane	83.50	4.60	73.30	93.22	5.52
FML/AtPt	8.24	6.21	-5.88	25.54	75.35
KW line/Md plane	-21.44	5.57	-35.82	-10.21	
NHA/PM plane	88.97	3.92	78.61	96.43	4.40
PM plane/PM vert	-4.77	2.56	-10.73	0.16	

Linear Variables (mm)	Mean	SD	Min	Max	CV
Ba-cv2ap	4.48	1.58	2.19	9.13	35.34
Ba-KW line	4.75	2.00	0.10	8.24	42.16
Ba-Op	35.08	3.26	28.92	44.69	9.29
At-Pt	46.18	2.55	41.06	51.21	5.52

Table 17. Descriptive statistics for males (N=19) for all angular and linear variables at T1

Angular Variables (°)	Mean	SD	Min	Max	CV
HOR/FH	-3.66	3.96	-10.35	5.91	
HOR/SN	4.89	4.54	-3.29	11.36	92.81
HOR/StN	7.88	4.47	-0.13	14.92	56.73
HOR/NHA	-5.30	4.62	-15.46	3.84	
HOR/KW line	-2.00	3.98	-11.15	4.78	
HOR/P plane	-0.04	5.03	-13.37	7.70	
HOR/FML	4.35	6.58	-8.43	16.24	151.44
HOR/AtPt	11.36	8.44	-5.81	28.04	74.30
HOR/FOP	-10.48	4.32	-22.52	-5.14	
HOR/Md plane	-23.59	6.67	-41.16	-10.49	
HOR/PM plane	84.37	4.91	69.44	90.47	5.82
FML/AtPt	7.01	5.36	-0.48	15.95	76.49
KW line/Md plane	-21.59	4.83	-30.01	-13.34	
NHA/PM plane	89.67	5.29	80.27	98.38	5.90
PM plane/PM vert	-5.79	1.91	-8.50	-2.22	

Linear Variables (mm)	Mean	SD	Min	Max	CV
Ba-cv2ap	4.78	1.95	1.58	9.06	40.90
Ba-KW line	5.11	2.77	1.24	11.38	54.24
Ba-Op	37.13	2.83	32.78	43.28	7.61
At-Pt	50.92	3.67	42.22	57.78	7.20

8.4.2 Sex Comparisons

F-tests were carried out to determine the any significant sex differences in variance for each variable. This was calculated by dividing the square of the larger male or female standard deviations by the smaller one (Table 18).

Table 18. Summary of male and female descriptive statistics comparison

	Females N=38		**Males N=19**		**M Vs F**		
Angular Variables (°)	**Mean**	**SD**	**Mean**	**SD**	***F* test**	***t*-test**	***p* value**
HOR/FH	-5.40	4.88	-3.66	3.96	1.51	1.35	0.18
HOR/SN	5.34	5.46	4.89	4.54	1.45	0.31	0.76
HOR/StN	8.38	5.44	7.88	4.47	1.48	0.35	0.73
HOR/NHA	-5.47	5.75	-5.30	4.62	1.55	0.12	0.91
HOR/KW line	-3.58	4.94	-2.00	3.98	1.54	1.21	0.23
HOR/P plane	-1.44	5.04	-0.04	5.03	1.00	0.99	0.33
HOR/FML	2.90	6.41	4.35	6.58	1.06	0.79	0.43
HOR/AtPt	11.06	7.37	11.36	8.44	1.31	0.14	0.89
HOR/FOP	-11.53	5.71	-10.48	4.32	1.75	0.71	0.48
HOR/Md plane	-25.02	6.96	-23.59	6.67	1.09	0.74	0.46
HOR/PM plane	83.50	4.60	84.37	4.91	1.14	0.66	0.51
FML/AtPt	8.24	6.21	7.01	5.36	1.34	0.74	0.46
KW line/Md plane	-21.44	5.57	-21.59	4.83	1.33	0.10	0.92
NHA/PM plane	88.97	3.92	89.67	5.29	1.83	0.56	0.57
PM plane/PM vert	-4.77	2.56	-5.79	1.91	1.80	1.54	0.13
Linear Variables (mm)	**Mean**	**SD**	**Mean**	**SD**	***F* test**	***t*-test**	***p* value**
Ba-cv2ap	4.48	1.58	4.78	1.95	1.53	0.63	0.53
Ba-KW line	4.75	2.00	5.11	2.77	1.92	0.56	0.58
Ba-Op	35.08	3.26	37.13	2.83	1.33	**2.34**	**0.02**
At-Pt	46.18	2.55	50.92	3.67	2.06	**5.69**	**0.00**

Significant values at the $p<0.05$ level are in bold

The *t* and *F* values illustrate no statistically significant differences between males and females except for Ba-Op and At-Pt which could be explained by sexual dimorphism. Therefore the data were pooled and descriptive statistics performed on this pooled sample (Table 19).

Table 19. Descriptive statistics for pooled females and males (N=57) for all angular and linear variables at T1

Angular Variables (°)	Mean	SD	Min	Max	CV
HOR/FH	-4.82	4.63	-17.12	5.91	
HOR/SN	5.19	5.13	-9.88	14.86	98.87
HOR/StN	8.21	5.10	-7.05	18.02	62.11
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	190.40
HOR/AtPt	11.16	7.67	-5.81	28.04	68.73
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	5.59
FML/AtPt	7.83	5.92	-5.88	25.54	75.62
KW line/Md plane	-21.49	5.29	-35.82	-10.21	
NHA/PM plane	89.20	4.39	78.61	98.38	4.92
PM plane/PM vert	-5.11	2.40	-10.73	0.16	

Linear Variables (mm)	Mean	SD	Min	Max	CV
Ba-cv2ap	4.58	1.70	1.58	9.13	37.22
Ba-KW line	4.87	2.27	0.10	11.38	46.59
Ba-Op	35.76	3.25	28.92	44.69	9.08
At-Pt	47.76	3.70	41.06	57.78	7.75

8.4.3 Pearson's Correlation Coefficients

Pearson's correlation coefficients were calculated to quantify the strength of the association between angular variables. These were calculated for male (N=19) and female (N=38) subjects at T1 for the angular variables shown in Table 20.

Table 20. Pearson correlation coefficients for angular and linear variables (males upper right, females lower left)

Angular Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
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 vert	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 are in bold

Correlation coefficients larger than 0.80 are bold. This was an arbitrary value of high correlation chosen such that $r^2 = 0.64$, i.e. 64% of the common variation is explained by the correlated finding. This is a strong correlation for a biological system.

8.5 Reproducibility of Natural Head Position

Reproducibility of the present study's natural head position technique was tested longitudinally. Thirty nine subjects were recorded photographically a second time in NHP at T2, 1.98 months (SD 1.09) after T1. The T2 photographs were used to transfer this second head position to the original lateral head tracing as per Section 7.8, and these tracings were then digitised to calculate all angular and linear variables. The HOR/SN variable was compared head positions at T1 and T2 through double determination. The data was first visualised for normal distribution (Figure 36 and Figure 37), followed by application of descriptive statistics. The mean difference (Mean diff), standard deviation of the difference (SD diff), paired *t*-test and Dahlberg value, S(i), were calculated (Table 21).

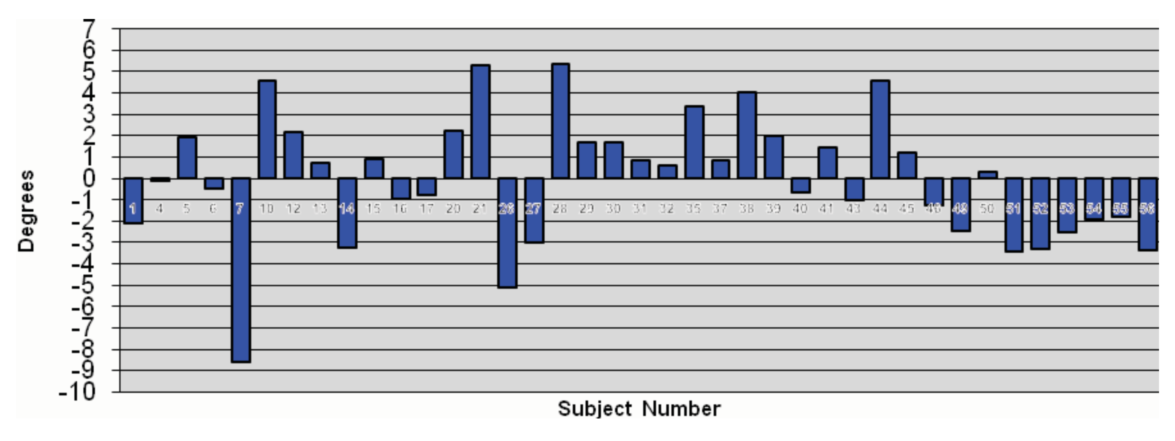


Figure 36. NHP reproducibility. Difference in HOR/SN values between T2-T1 (°)

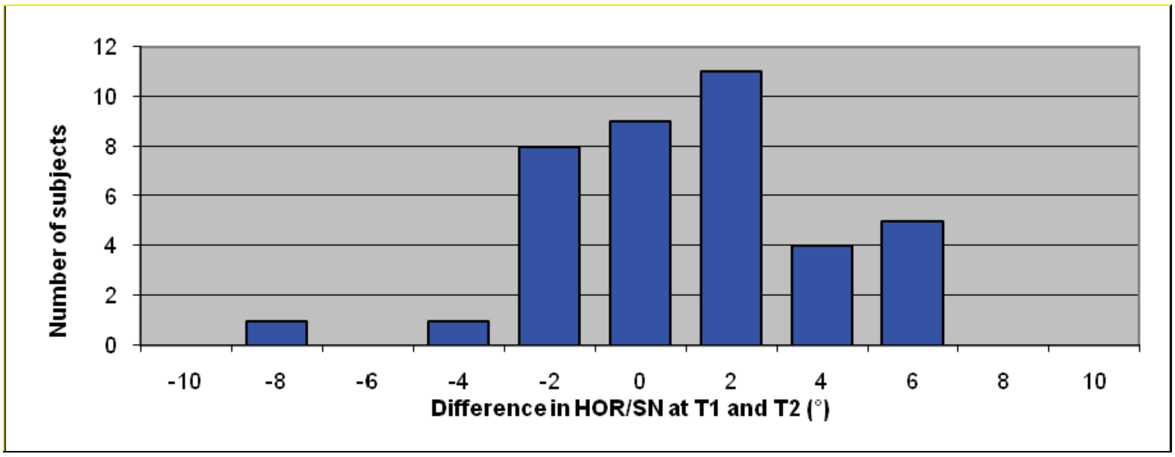


Figure 37. Distribution of data for NHP reproducibility

Table 21. Reproducibility of natural head position as determined by double determinations at T1 and T2 (N=39)

Angular variable (°)	N	Mean diff	SD diff	*t* test	*p* value	S(i)
HOR/SN	39	-0.0004	2.99	0.0008	0.9993	2.08

The results in Figure 37 display a central tendency about zero. However, subject number 7 (Figure 36) showed a large lowering of the head at T2 compared to T1 by more than two standard deviations from the mean. According to the Dahlberg value, the reproducibility of NHP was 2.08° in the present investigation.

9. Discussion

9.1 The Sample

9.1.1 Sample Size

Fifty seven subjects were included in the present study for data analysis at T1. The statistical power for this sample size was 0.82 at $p<0.05$. The two outliers were kept in the study to maximise sample size. Other commonly cited investigators testing the variability of craniofacial reference planes have used similar sample sizes [2, 15, 40, 41] (Table 1). Thirty nine subjects were followed up at T2 to assess the reproducibility of natural head position in the present study. The power test of 39 subjects to determine the reproducibility of NHP was 0.99 at $p<0.05$ which is sufficient.

There was a high drop out of subjects between T1 (N=57) and T2 (N=39). The reasons for this are outlined below.

- To minimise the impact of study participation, and increase participation rate, it was decided that the follow up photograph at T2 be coordinated with normal orthodontic treatment appointments. This meant that the T1 photograph, T1 lateral head radiograph, and T2 photograph were all collected on appointments that were otherwise required for the subject's orthodontic care. This minimised any inconvenience to the participants, however meant that the author could not always coordinate treating his own clinical patients, and collecting follow up T2 data for the present study (15 subjects)
- Subjects decided not to go ahead with treatment after pre-treatment record collection (2 subjects)
- Subject failed to attend multiple appointments (1 subject)

9.1.2 Sample Sex Distribution

Subject data collection was performed consecutively with no effort made to collect even numbers of males and females. It is interesting to note at T1, there were 38 female subjects and 19 males. And at T2, there were 25 females and 14 males. At both time points, the ratio of females to males was about 2:1 which is representative of the estimated orthodontic patient population at the Adelaide Dental Hospital and private practice experience.

9.1.3 Observation times

The mean time periods from lateral head radiograph exposure to T1 photograph and T1 photograph to T2 photograph were 0.1 and 2.1 months respectively (Table 13 and Table 14). Both of these time periods are likely to be sufficiently short enough to have minimal growth changes in profile between the lateral head radiograph to the photograph. Therefore growth is unlikely to contribute much to the method error in the vertical plumbline transfer process from photograph to cephalometric tracing.

The time period from T1 to T2 natural head position registrations was an average of 2 months. This period of time was felt to be sufficiently long enough to reduce any patient memory or practice bias at the T2 registration. It can therefore be assumed that, the NHP registrations at T2, were not influenced by the registration at T1.

9.2 Method Error and Limitations

The results of any cephalometric study should always be interpreted within the context of the amount of method error that may be contributing to the result. Should the method error be larger than the actual measurement, then the result, even if statistically significant, can not be clinically significant.

The present study employed a number of steps during which a small degree of error was anticipated. A number of factors contributed to the method error of the present study.

9.2.1 Radiographic Limitations

Cephalometric radiographs used in the present investigation were obtained from the same location with the same machine. However, the operators taking the radiographs were different undergraduate students and, therefore, standardisation of technique and settings cannot be assumed. The consequence of this is that there may have been some scope for altered head position in the cephalostat and patient mandibular position which may affect the location of craniofacial structures on the radiograph.

Additionally, mid-way through the collection of subjects, the Radiography Department changed from traditional wet film processing to dry digital plate film plate processing. The resultant cephalometric films were of moderate quality, with reduced contrast and low resolution. The post-image exposure digital processing prior to film printing was also performed by different radiographic staff and the results were sometimes quite varied with regard to image quality. These factors, no doubt, affected the error inherent in landmark identification on the lateral cephalometric films. To minimise any further radiographic error, a single operator traced and digitised all films.

An additional radiographic problem was one of film scale determination on the films when digitising in the Mona Lisa Craniofacial software. The overly small digital phosphor film plate tended to produce cephalometric films that had sometimes up to 30 mm of the 45 mm calibration ruler cropped off (Figure 38). For this reason, a full 45 mm ruler from a film taken in portrait view was transferred to each digital film tracing (N=48 subjects). Regardless of the method error associated with determining the linear variables in Section 7.9.5, the results for linear variables should be considered with caution and may not be a true representation of actual measurements.

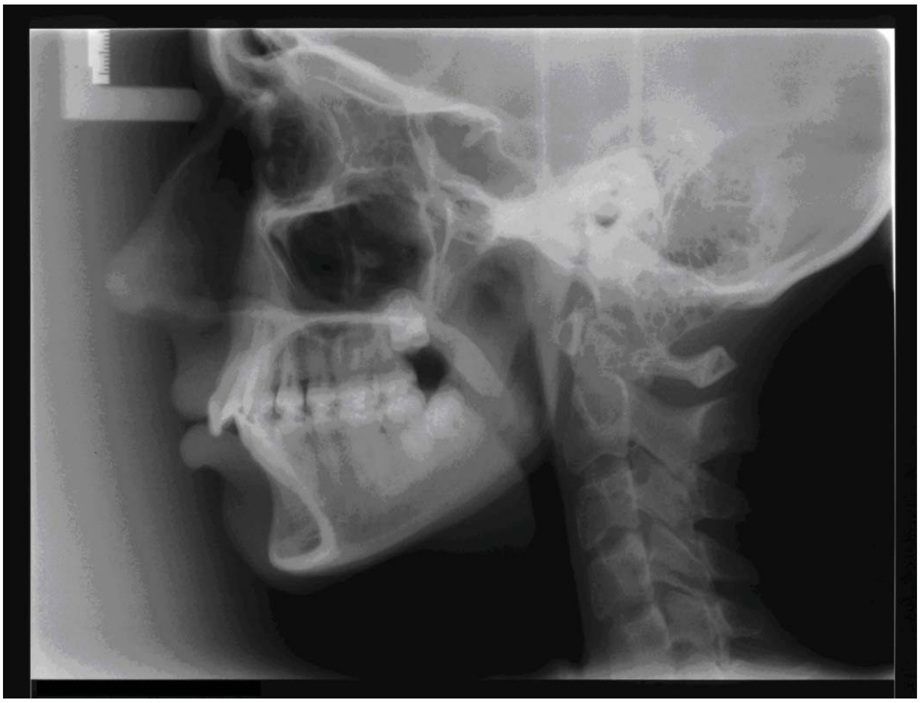


Figure 38. Cropped calibration ruler

Another consequence of small radiographic films was that in order to get an image including all the required anatomy for analysis, patient head orientation needed to be lower than it would normally be during radiographic exposure. This produced soft tissue bunching at the chin-throat region of each subject’s soft tissue profile (Figure 20). However, it is unlikely that this affected the method error because the plumbline transfer and cephalometric analysis carried out did not involve these structures. An additional consequence of such radiographic head positioning was the cervical spine to cranial base relationship was altered. Because of this, it was decided to abandon any investigations involving natural head posture, i.e., angular measures from cervical spine to cranial structures.

9.2.2 Limitations of Method

Despite multiple investigations advocating the use of NHP in preference to conventional craniofacial reference planes [2, 4, 7], the use of NHP as a craniofacial system still remains limited. Bister et al [86] suggests the reasons for this might be,

- Confusion over terminology and methodology in achieving NHP
- Lack of reliable reference data

- Taking radiographs in NHP may be more time consuming and operator sensitive than conventional methods

In the present study, it was found that using NHP in cephalometric analysis did involve additional steps that would otherwise not be needed if conventional cephalometric analysis was carried out.

Firstly, a standardised photographic rig was set up as described in Section 7.5.2. The additional equipment for this rig included a $500 tripod, a wall mounted plumbline and wall mounted mirror.

Secondly, a standardised photographic protocol must be used to achieve NHP (Section 7.6), which, in the context of orthodontic practice, requires staff training. A decision as to whether a “corrected” natural head orientation be used in unnatural head postures would also need to be made. It was also found that when subjects were being prepared for NHP registration, making subjects walk forward tended to make them lose eye contact from the mirror to the ground momentarily. This may confound the resultant head orientation.

Additional photographic processing and VER transfer were also required prior to cephalometric measurements (Section 7.6-7.8). In the present study, these additional computer-based image processing steps were performed manually in Adobe Photoshop CS. However, there would no doubt be potential for these computer steps to be integrated into a cephalometric software package.

Despite the additional steps required for the clinical application of NHP, there were positive aspects that were observed during the data collection phase of the present study. Firstly, the photographic rig was simple in design and easy to use. Also most subjects understood the procedures required for NHP registration, and there seemed to be minimal scope for misunderstanding. The VER transfer process (Section 7.8) was surprisingly simple and accurate (Section 8.2.3). These aspects limit the additional impact of adopting NHP in clinical practice.

9.2.3 Error Associated With Cephalometric Software

Most studies assume that digitising software packages are accurate and perform better than normal measurement. However, this is rarely tested. The present investigation used a new software package that had not been used in the department before and therefore, was validated to be an accurate form of measuring cephalometric film tracings. The reference measurements were calculated using trigonometry applied in a grid of squares (Section 7.11.1). The software measurements proved to be very accurate. The mean angular measurements differed from the actual values by only 0.05° and the linear measurement was exactly the same (Table 8). The reliability of these measurements was excellent considering that the same measurements repeated 10 times only produced a standard deviation of 0.06°. It would seem very unlikely that the software used to measure angular and linear variables contributed to error of the overall method. It would also suggest the operator placed the cursor with a high degree of precision.

9.2.4 Error of The Overall Method

The overall method as outlined from Section 7.6 to 7.9 included photographic registration of NHP, cephalometric film tracing and digitising, true vertical transfer and software measurement of angular/linear variables. One may criticise the present method to be flawed by too many steps, thus accumulating the error inherent with each step. However, in its defence, most of the steps were computer hardware and software based which are often as accurate as the operator using them.

To determine the error associated with the above methods, 20 sets of records were selected at random to perform double determinations (Section 7.11.2). Systematic errors were determined by calculating the mean diff, SD diff, paired *t*-test, and *p* value for each variable. Random errors were determined by calculating S(i), E(var) and reliability. The results in Table 9 illustrate some statistically significant systematic errors associated for the following variables

- HOR/KW line ($p<0.01$)
- HOR/P plane ($p<0.05$)
- HOR/FOP ($p<0.05$)
- FML/AtPt ($p<0.05$)

- Ba-Op ($p<0.05$)
- At-Pt ($p<0.05$)

And random error associated with the linear variable,

- Ba-cv2ap (<90% reliability)

Houston [93] highlights that such systematic errors are a likely result of the observer's practice changing with experience. This is a likely contributing factor in the present study. The angular variable HOR/KW line had a significant ($p<0.01$) systematic error that was about 0.5° mean reduction at the second determination. This trend was also illustrated in the HOR/P plane angular variable which illustrated a significant ($p<0.05$) systematic mean reduction of about 0.8° at the second determination. It would seem that the KW line and P plane were inclined more horizontally at the second determination. This forward rotation of planes was not replicated in other horizontal planes, which suggests a change in observer practice at the second determination.

The direction of systematic error associated with HOR/FOP was opposite with a mean increase of 0.8° at the second determination ($p<0.05$). It is likely that the method to construct the functional occlusal plane (FOP) altered between determinations. The angular variable FML/AtPt showed a systematic mean increase of 0.4° between determinations ($p<0.05$). The curved nature of the landmarks that construct these planes allow scope for different interpretation between determinations. The linear variables with systematic error were Ba-Op and At-Pt which showed a mean decrease of 0.6 mm ($p<0.05$) and mean increase of 0.3 mm ($p<0.05$) respectively. It is difficult to account for these small changes.

Also in the absence of double blinding, bias can be introduced because the single operator is aware that they are performing the second series for the double determinations, and thus may do so slightly differently from the first series.

One way to control such bias is to randomise the order in which the records are measured, ideally preventing the measurer from know which record belongs to a particular group [93]. Such blinding was not performed in the present study.

It is worth noting that the systematic errors observed in the present investigation are at most, a mean value of 0.8° for angular measurements and 0.6 mm for linear measurements. Both of these are small and, therefore, it could be argued, not clinically significant. However, more importantly there were some variables that showed statistically significant errors. Therefore the results for these variables should be considered with the degree of associated error in mind.

Even when performing double determinations on the same film, errors associated with landmark identification should not be ignored [95]. This is often one of the largest contributors to random error either due to identification or imprecision in its definition [93]. Other factors that affect random errors include that of film contrast and sharpness. In the present investigation, Ba-cv2ap showed some random error which may be attributed to both Ba and cv2ap being difficult to locate, due to the lack of contrast in the films and the superimposition of these structures with other anatomical features.
The Dahlberg values for all angular variables range from 0.49° to 1.28° which is a clinically acceptable level of random error.

9.2.5 Error of The Vertical Plumbline Transfer

One of the aims of the present study was to establish a method for transferring the true vertical line from a lateral head photograph to a lateral head cephalogram (Section 6). A digital method for performing this was developed and outlined in Section 7.8 as a part of the present investigation. The materials for this method were easily obtained and relatively inexpensive (modern PC computer and Adobe Photoshop CS).

Adobe Photoshop CS utilises layers to superimpose graphical elements like clear transparencies layered on top of one another. This feature was used to in the present method to layer the cephalometric tracing over the lateral head photograph. It is also a vector based graphics program that allows the simple and proportional resizing and rotating of the cephalometric tracing layer such that it can be accurately superimposed over the head photograph.

The superimposition between cephalometric tracing and lateral head photograph was performed using the profile outlines of the nose and forehead. These structures were chosen due to the variable nature of other soft tissue structures such as the chin, which is influenced by mentalis activity, and the lips, which are also quite varied in strain and posture.

Previous investigators who have used a photographic method of NHP and transfer of the true vertical plane have adopted methods which use the chin. Lundström & Lundström essentially relied on the use of the constructed soft tissue nasion (N') to soft tissue pogonion (Pog') line for comparison between cephalogram and photograph (Figure 17)[32]. Subsequently, Ferrario and co-workers used the same system except they simply transferred the angular difference between N'-Pog' and VER from the photograph to the cephalometric tracing[96]. Leitão & Nanda were the first to use the E plane to VER angle to transfer head orientation from photograph to cephalometric tracing (Figure 39)[17]. This was subsequently adapted by Bass, 2003[97].

Figure 39. E plane to VER angle to transfer true vertical from photograph to cephalometric tracing[17]

It is worth noting that none of these investigators who used a photographic registration of NHP tested the error associated with this step of their technique and, therefore, it may be difficult to validate their transfer of true vertical process. The investigators[17, 32, 96, 97] did, however, give a report of their overall method error which often wasn't described clearly. A brief outline is below in Table 22.

Table 22. Method error of studies employing transfer of VER

Author	Systematic error	Random error	Limitations
Lundstrom & Lundstrom, 1992 [15]	head raised 1° p<0.01	Dahlberg 1.8°	description vague
Ferrario et al, 1994 [96]		about 3% of measurement value	description vague, did not include VER transfer
Leitão & Nanda, 2000 [17]	*t* test, not significant for all variables	Dahlberg < 1°/mm	description vague
Bass, 2003 [97]			No method error performed

The transfer of the vertical plumbline from lateral photograph to lateral cephalometric tracing was a single step in the overall method of the present study. The method error of this step was determined to validate the technique used. The same 20 subject tracings from the previous error study (Section 9.2.4) were re-superimposed to their respective photographs as per Section 7.8 at least one month later. This produced an orientation of the lateral cephalogram tracing over its corresponding photograph on two separate occasions, which was then used for double determinations. On each occasion, a reference plane was compared with true horizontal.

The results showed that the error of plumb line transfer in the present study was quite low (Table 10). A *p* value of 0.26 and Dahlberg value of 0.43° are very good results given that the nasal profile in two of the subjects was distorted from being pressed up against a reference ruler, making the superimposition of tracing and photograph more varied in these two subjects (Figure 40). An additional limitation was the small lateral head film often had minimal forehead profile to superimpose on, or hair may be covering the subjects profile in this region. Despite this, the results indicate that the method of nose and forehead superimposition is a valid method of transferring VER from photographic NHP registration to cephalometric tracing.

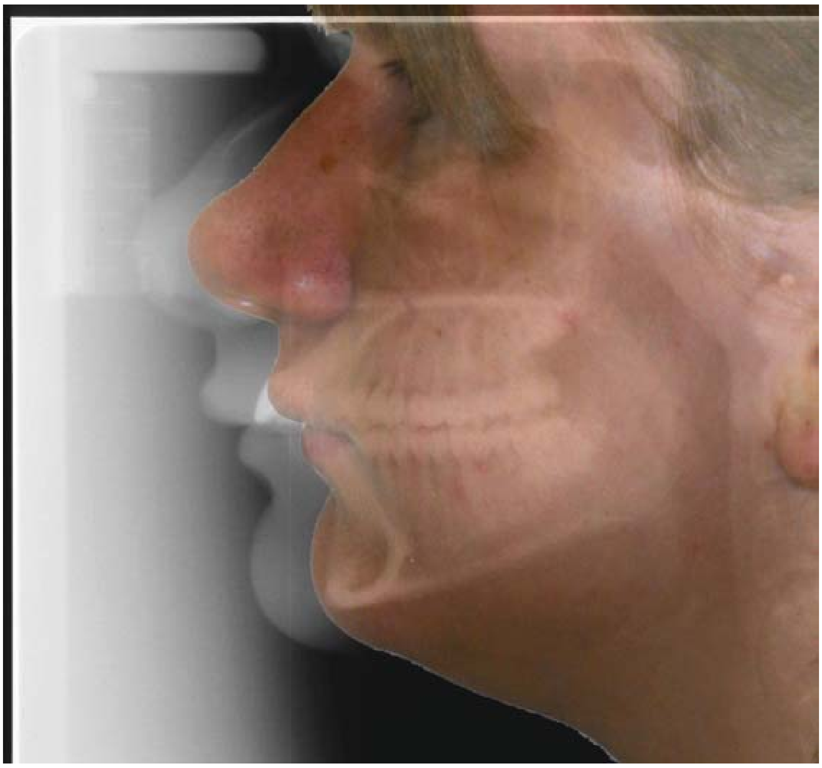


Figure 40. Nasal profile distortion and minimal forehead profile affecting VER transfer (N=2)

9.3 Variability of Craniofacial Reference Planes

When testing the data for normality, the visual box plots in Figure 34 and Figure 35 illustrate one or two subjects who were possible outliers for most variables. While these subjects may alter the data in a particular (additional or subtractive) direction, variable head posture and craniofacial structure orientation is expected. For this reason, these subjects were not excluded from the processed data for statistical analysis. Additionally, with a statistical power of 82% when male and female subjects are pooled (N=57), it was felt that exclusion of further subjects would lower the power of statistical analysis to a less acceptable level.

In the present study, the inter-individual variability of craniofacial reference planes to HOR is expressed by standard deviations, ranges and coefficients of variation. For the angular variables, males and females showed a similar range of standard deviations of 1.91° to 8.44° and 2.56° to 7.37° respectively. The linear variables also showed this similarity with standard deviations for males and females of 1.95° to 3.67° and 1.58° to 3.26° respectively.

When the data were tested for sex differences using *F* and *t* tests (Table 18), no significant differences were found between males and females for all variables except the linear variables Ba-Op ($p<0.05$) and At-Pt ($p<0.01$). This may suggest that males have larger foramen magnum and 1st cervical spine length dimensions than females. However this association may be masked by a degree of systematic error that was illustrated with these two variables as shown in Table 9. With little difference between males and females, the data were pooled to the sample size of 57 subjects for descriptive statistics as shown in Table 19. These pooled data are considered by average orientation, variability of planes and correlation between planes.

9.3.1 Angular Variables Involving HOR

Firstly, average orientation of craniofacial reference planes to HOR is considered. Previous investigators have often compared SN and FH to HOR or VER [2, 4, 5, 7, 15-17, 34-38, 40-42]. The mean values for variables HOR/FH and HOR/SN were -4.82° and 5.19° respectively. This indicates that for the present investigation, on average, true horizontal lay in between FH and SN by nearly the same amount, with the inclination of SN above, and FH below HOR. Therefore, the mean SN/FH angle can be interpreted from this as being almost 10°, which is larger than other published data of 7° [2, 4]. Though this inclination may suggest a more vertical nature of the present sample, the interpreted mean SN/Md plane angle is about 30° which contradicts this notion. The increased SN/FH may perhaps be a landmark recognition difference at the points that construct these planes, such as a consistently higher position of porion. Given that porion is superimposed on its external, internal, left and right side structures, this would seem likely. However, there were no significant systematic or random errors associated with SN or FH, so the author remained consistent with landmark recognition in the present study.

A comparison between studies of variables HOR/FH and HOR/SN is illustrated below in Table 23.

Table 23. Comparative data for variables HOR/SN and HOR/FH (adapted VER/SN and VER/FH data)

		HOR/SN (°)		HOR/FH (°)	
Author, Year	**n**	**Mean**	**SD**	**Mean**	**SD**
Downs, 1952 [34]	100			-1.9	5
Downs, 1956 [5]	100			-2.3	5
Bjern, 1957 [4]	35	4.3	3.99	-2.8	4.6
Moorrees & Kean, 1958 [2]	61	4.7	3.9	-2.21	4.02
Solow & Tallgren, 1971 [7]	120	2.6	4.2		
Siersbæk-Nielsen & Solow, 1982 [35]	30	8.42	5.1		
Cole, 1988 [36]	20	3.6	7.6	-0.1	9.1
Tallgren & Solow, 1987 [37]	81	9.6	3.58		
Sandham, 1988 [38]	12	3	5		
Cooke & Wei, 1988 [39]	120	6.8	5.6		
Lundström & Lundström, 1992 [32]	27	3.8	5.6	-5.1	5.3
Huggare, 1993 [40]	28	8.6	5.2		
Lundström & Lundström, 1995 [41]	39	2.6	5.4	-1.6	5.2
Solow & Sonneson, 1998 [42]	96	6.3	6.1		
Leitão & Nanda, 2000 [17]	284	8.19	4.45	-0.73	5.02
Barbera etal, 2005 [94]	40	7.4	5.55	-1.6	4.85
Present study	57	5.19	5.13	-4.82	4.63

It is interesting to note how the mean values for HOR/SN and HOR/FH are quite variable between studies. One is left to assume that these differences are due to sample morphology differences and operator factors.

In addition to these two planes, the present study investigated the variability of nine other planes in relation to true horizontal.

It is not surprising that HOR/StN had a mean value slightly larger than HOR/SN of 8.2°, given the close interrelationship between sella and the sella tangent points.

NHA was inclined about -5° below horizontal in the present study. Though McCarthy & Lieberman's work [31] did not compare NHA to HOR, Barbera [94] found that NHA in a sample of 40 aboriginal subjects was -0.9°.

HOR/KW line, on average, was -3° below horizontal. The Krogman-Walker plane was developed as a horizontal plane for orientation for lateral head tracings [18]. The previous investigations by Barbera [94] illustrated that this plane was -0.2° in the aboriginal sample.

The palatal plane was also inclined -1° below horizontal in the present study, which is in agreement with previous investigations that found HOR/P plane to be associated with a mean value of -0.5° to -5.45° [7, 16, 17, 42, 94].

On average the foramen magnum line, FML was positively inclined to HOR by 3.4°. This implies that basion was generally higher than opisthion, a finding consistent with Barbera's work.

The orientation of AtPt was 11° positive to HOR while found to be 16° in Barbera's work. However given the methodological issues with unnatural downward head tip at radiographic exposure (Section 7.4), it is felt that few conclusions can be drawn from this.

The functional occlusal plane (FOP) showed a mean downward inclination of -11° to HOR, a result comparable to Barbera's sample finding of -11°.

As expected, the mandibular plane was directed -25° below horizontal which gives some indication as to the average mandibular morphology compared to true horizontal.

HOR/PM plane was found to be 84° in the present study which differed by 5° from Barbera's finding of 89°.

The differences between Barbera's results (with mandibles in occlusion) and the present study are summarised in Table 24. Most of the angular variables suggest that the head positions of the present sample are a few degrees lower than Barbera's. Additionally, it is interesting to note that although the mean values differ sometimes greatly, the standard deviations are remarkably similar. This trend seems consistent when comparing other studies as well (Table 23). These differences may be attributed a number of factors listed below,

- Barbera's sample included an Aboriginal population while the present sample was predominantly of mixed ethnic Caucasian backgrounds. This may have implications for the average craniofacial morphology of the two samples.
- The radiographic equipment was different between studies with different film sizes and quality.
- Head positioning. The Barbera sample cephalometric films were exposed with patients looking at an object at eye level during film exposure while the present study used a photographic mirror guided technique.
- Although the same definitions for each landmark were used, it is likely that there were some operator differences in interpretation.

Table 24. Comparative data between the present study and Barbera's work [94]

NOTE: This table is included on page 103 of the print copy of the thesis held in the University of Adelaide Library.

The inter-individual variability of craniofacial reference planes compared to HOR is largely described by standard deviation values in the present study (Table 19). However, other measures of variability include the range (Min-Max), coefficient of variation for positive values (CV), and the visual box plot distribution of subjects for each variable (Figure 34).

Firstly, the standard deviation of craniofacial reference planes related to HOR in Table 24 ranged between 4.63° and 7.67°. Of these angular variables, there was no single plane that stood out as having a much lower standard deviation than the other. HOR/FH had the lowest standard deviation of 4.63° and similarly, HOR/KW line 4.67°. In other words, the craniofacial reference planes FH and KW line showed the lowest variance in the present study. Placing this in context, however, is the fact that five other planes (SN, StN, NHA, P plane, and FOP) all had standard deviations within 1° of these two planes. Therefore it would seem, that most planes exhibited a similar inter-individual variability to HOR. Interestingly, when compared with the previous work of Barbera, 2005 [94], similar trends are seen. In both studies the largest standard deviation was observed in HOR/AtPt and the least in HOR/FH and HOR/KW line. However, there was also no reference plane with clearly lower variability to HOR than any other.

Secondly, the ranges observed in angular variables involving HOR are sizable (Table 19). The angular variables HOR/FH, HOR/KW line and HOR/P plane showed the lowest ranges of 23°, 23° and 22° respectively. While angular variables HOR/AtPt and HOR/Md plane showed the largest ranges of 34° and 32° respectively. This is not surprising as the Md plane varies significantly with facial morphology and AtPt fluctuates with head posture. These results highlight that the range of each variable only differs by about 10° between the smallest and largest ranges, suggesting a similar degree of variation for all variables. This seems consistent with the observed standard deviation values. The observed ranges in Barbera's work were of similar magnitude [94]. HOR/FH, HOR/KW line and HOR/P plane ranges were 20°, 19°, and 20° respectively. While HOR/AtPt and HOR/Md plane ranges were 36° and 20°.

Thirdly, observed coefficients of variation (CV) in the present study were only calculated for positive values (Table 19). HOR/FML showed the highest value (190.40 %) while HOR/PM plane was the lowest (5.59 %). One should be careful interpreting these results, however. CV is calculated as a percentage of the standard deviation divided by the mean. Given that most variables have similar standard deviation values, it would seem that CV is largely influenced by the magnitude of the mean value. HOR/FML and HOR/PM plane have largely differing means of 3.39° and 83.79° respectively. Table 25 compares the coefficients of variations observed in the present investigation with those found by Barbera [94]. Interestingly, the smallest value was also HOR/PM plane for the reasons outlined above.

Table 25. Comparative data illustrating coefficients of variation

	Coefficient of variation (%)	
Angular Variables (°)	**Present study**	**Barbera, 2005 [94]**
HOR/FH		
HOR/SN	98.87	74.92
HOR/StN	62.11	57.01
HOR/NHA		
HOR/KW line		
HOR/P plane		
HOR/FML	190.40	71.25
HOR/AtPt	68.73	56.01
HOR/FOP		
HOR/Md plane		
HOR/PM plane	5.59	6.42
FML/AtPt	75.62	118.17
KW line/Md plane		
NHA/PM plane	4.92	4.07
PM plane/PM vert		133.23

Linear Variables (mm)	**Present study**	**Barbera, 2005 [94]**
Ba-cv2ap	37.22	1.70
Ba-KW line	46.59	2.27
Ba-Op	9.08	3.25
At-Pt	7.75	3.70

And finally, box plot distributions in Figure 34 are a graphical representation of the data and their dispersion. For each variable, the median, 1st and 3rd quartile, inner fences (1.5 upper and lower hinge) and outside values are illustrated. From visual inspection, although it would seem that HOR/AtPt and HOR/Md plane have the largest spread, all the remaining variables appear to have a similar size between upper and lower inner hinges. This further strengthens what the other representations of data suggest, that there was no variable compared to HOR with clearly low variation.

Additionally, some of the angular variables compared to HOR showed a high Pearson correlation with another (Table 20). The highly correlated variables for both male and females are outlined below (r >0.80). These were all positively correlated i.e., as one variable increases, so does the other.

- HOR/FH with HOR/NHA and HOR/KW line

  The relationship between FH and NHA can partly be explained by the anterior construction of both these planes utilising the orbit. This anatomic interdependence is probably the largest contributor to the strength of association found here.

The strong association of HOR/FH and HOR/KW line is an interesting one, however. The posterior construction of these two planes is quite different in anatomical location. While the anterior construction points are in the maxilla, they too are in quite different locations. Despite this, these variables were highly correlated for both males and females with *r* values of 0.91 and 0.88 respectively. This suggests there is consistent spatial relationship between these planes which might largely be driven by the morphology of the maxilla which is common to these three variables. Given that the airway passes between the landmarks that are used to construct FH and KW line, the functional requirement of respiration may be related to this morphological consistency.

- HOR/SN with HOR/StN and HOR/NHA

  It is not surprising that HOR/SN and HOR/StN have correlation coefficients of 1.00. Both SN and StN planes utilise a common landmark and even posteriorly, share the same structure (pituitary fossa).

  The strong association between HOR/SN and HOR/NHA can be justified by the closely related construction point at the pituitary fossa.

- HOR/StN with HOR/NHA

  The plane StN being so related to SN, it would be expected that any association with HOR/SN above, would also be observed in the associations with HOR/StN. Once again, the pituitary fossa is the common contributing factor to the anatomic interdependence observed.

- HOR/NHA with HOR/KW line

  Despite there being no obvious shared anatomical landmarks between NHA and KW line there was a strong association with these variables. In a similar fashion to the association found with HOR/FH and HOR/KW line, one may conclude this to be a consistent morphological feature or perhaps a spurious correlation come about by the sample sizes being too small. There is some possibility of spurious correlations occurring because the separate sex sample sizes are limited (females 38, males 19).

- HOR/KW line with HOR/FH and HOR/NHA
  As discussed above.

9.3.2 Angular Variables between Intracranial Planes

Of the angular variables constructed using intracranial reference planes, a few interesting trends were elucidated from Table 24.

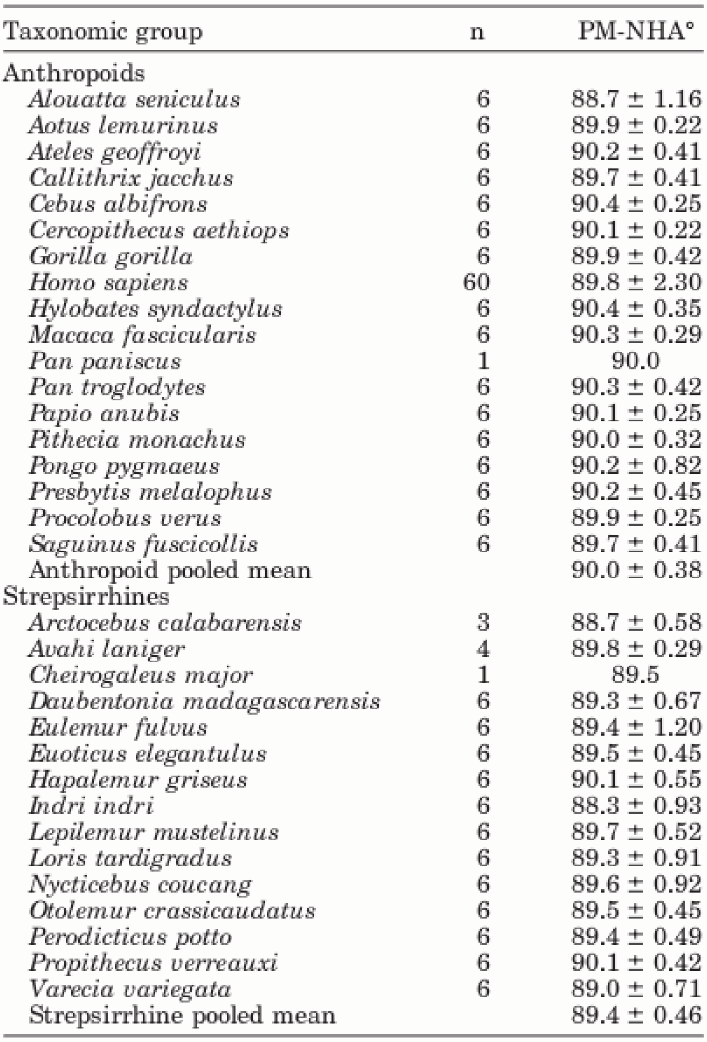
FML/AtPt had a relatively low mean due to the interrelationship between foramen magnum and the first cervical vertebra while it displayed a larger standard deviation due to the range of head postures that were observed in the present sample.

KW line/Md plane illustrated a standard deviation of 5.3° which was similar to most of the variables involving HOR.

NHA/PM plane displayed a mean and SD of 89.20° and 4.39°, respectively. This interesting finding confirms the works of previous investigators [30, 31, 98]. In 1975, Enlow [30] suggested that the PM plane maintains a constant 90° angle with the NHA of the orbits in lateral head radiography. McCarthy & Lieberman [31] later tested this hypothesis in anthropoids and strepsirrhines. They found the mean NHA/PM plane angle to be remarkably close to 90° with low standard deviations (Table 26). The results of the present study are also comparable to Barbera's, who found the mean and standard deviation for NHA/PM plane to be 90.2° and 3.67° respectively [94] (Table 24). There have been little data presented to suggest why this relationship should exist. McCarthy & Lieberman [31] felt that one possibility is that a constant 90° NHA/PM plane angle may be a structural adaptation to maintain a constant shape of the airway during growth. A 90° NHA/PM plane aligns the oral and nasal cavities , which lie anterior to the PM plane, in a constant orientation relative to the nasopharynx and oropharynx, which lie posterior to PM plane, thereby preserving spatial relationships between the nasal, oral and pharyngeal parts of the airway. Perhaps this may suggest a structural consistency in the sphenoid which contains the optic canals and has the vertical pterygoid plates.

PM plane/PM vert naturally illustrated a low standard deviation given the closely related structures that produce these planes. In the present investigation, PM plane was rotated 5° to PM vertical in a clockwise direction when the subject is facing left. Interestingly however, Barbera [94] found PM plane to be rotated in the opposite direction by 2°. It may be difficult to compare these two results given the sample differences.

Table 26. McCarthy & Lieberman's dry skull results for NHA/PM plane [31]



Taxonomic group	n	PM-NHA°
Anthropoids		
Alouatta seniculus	6	88.7 ± 1.16
Aotus lemurinus	6	89.9 ± 0.22
Ateles geoffroyi	6	90.2 ± 0.41
Callithrix jacchus	6	89.7 ± 0.41
Cebus albifrons	6	90.4 ± 0.25
Cercopithecus aethiops	6	90.1 ± 0.22
Gorilla gorilla	6	89.9 ± 0.42
Homo sapiens	60	89.8 ± 2.30
Hylobates syndactylus	6	90.4 ± 0.35
Macaca fascicularis	6	90.3 ± 0.29
Pan paniscus	1	90.0
Pan troglodytes	6	90.3 ± 0.42
Papio anubis	6	90.1 ± 0.25
Pithecia monachus	6	90.0 ± 0.32
Pongo pygmaeus	6	90.2 ± 0.82
Presbytis melalophus	6	90.2 ± 0.45
Procolobus verus	6	89.9 ± 0.25
Saguinus fuscicollis	6	89.7 ± 0.41
Anthropoid pooled mean		90.0 ± 0.38
Strepsirrhines		
Arctocebus calabarensis	3	88.7 ± 0.58
Avahi laniger	4	89.8 ± 0.29
Cheirogaleus major	1	89.5
Daubentonia madagascarensis	6	89.3 ± 0.67
Eulemur fulvus	6	89.4 ± 1.20
Euoticus elegantulus	6	89.5 ± 0.45
Hapalemur griseus	6	90.1 ± 0.55
Indri indri	6	88.3 ± 0.93
Lepilemur mustelinus	6	89.7 ± 0.52
Loris tardigradus	6	89.3 ± 0.91
Nycticebus coucang	6	89.6 ± 0.92
Otolemur crassicaudatus	6	89.5 ± 0.45
Perodicticus potto	6	89.4 ± 0.49
Propithecus verreauxi	6	90.1 ± 0.42
Varecia variegata	6	89.0 ± 0.71
Strepsirrhine pooled mean		89.4 ± 0.46

9.3.3 Linear Variables

Males were found to be significantly larger than females for the linear variables Ba-Op and At-Pt (Table 18). This suggests that in males the foramen magnum opening is larger and the first cervical vertebra is larger the anteroposterior dimension. This sexual dimorphism is not surprising. It may be difficult to extrapolate any other implications from these differences given that there were few linear variables measured and the systematic method error associated with these variables (Table 9). The standard deviations for linear variables in the present study are surprisingly similar to those found in Barbera's sample [94] (Table 24).

9.4 Reproducibility of Natural Head Position

The intra-individual reproducibility of NHP is essentially a measure of an individual's ability to reproduce the same head position on successive occasions. The recorded natural head position in the present study was tested for reproducibility as per Section 7.10. This was performed by recording NHP on two separate instances for each subject (T1 & T2), then comparing these head orientations. This comparison was performed for one variable, HOR/SN, which was chosen for its clear landmark identification and therefore reduced method error. These determinations were performed for 39 subjects which provided sufficient statistical power (Section 8.1.2). The time period between head registrations was 1.98 months (SD 1.09) and felt to be sufficient.

The results in Section 8.5 indicate that the reproducibility for the mirror guided head position used in the present study was reasonable, and comparable to previous work. The mean difference between determinations was zero and not significant (Table 21). However, the distribution of results in Figure 38 illustrates the variation of reproducibility of NHP. The numerical representation of this reproducibility is also presented as a SD diff and Dahlberg value of 2.99° and 2.08° respectively.

The reproducibility of NHP in the present study is comparable to previous works that found the reproducibility of a mirror guided NHP to be associated with Dahlberg value of 2-3° (Table 27).

Table 27. Comparative data for reproducibility of NHP

	Double determinations (°)			
Author and Year	**n**	**S(i)**	**Mean range**	**SD diff**
Bjern, 1957 [4]	35		2.26	1.34
Moorrees & Kean, 1958 [2]	66	2.05		
Carlsoo & Leijon, 1960 [87]	17	4.6		
Solow & Tallgren, 1971 [7]	21	1.43		
Frankel, 1980 [88]	923		2.44	2.03
Foster, 1981 [89]	8		4.1	
Siersbaek-Nielsen & Solow, 1982 [35]	30	2.25		
McWilliam & Rausen, 1982 [81]	15	1.8		
Lyuk, 1986 [90]	18	4.9		
Cole, 1988 [36]	8	2.18		
Cooke & Wei, 1988 [16]	30	1.9		
Sandham, 1988 [38]	12	3.2		
Cooke, 1990 [12]	30	3.04		
Lundstrom & Lundstrom, 1992 [15]	27	1.8		
Huggare, 1993 [40]	33	1.6		
Peng & Cooke, 1999 [13]	20	2.23		
Bister et al, 2002 [86]	65	3.24		
Usumez & Orhan, 2003 [91]	20	1.1		
Present study	39	2.08		2.99

As illustrated above, the vast majority of investigators have presented their data for NHP reproducibility as a Dahlberg value. Bister et al [86] highlighted that despite its widespread use, the Dahlberg formula has a tendency to camouflage the true variability of results. Therefore, they advocated the use of the reproducibility coefficient and its graphical representation for NHP reproducibility assessment. Figure 36 and Figure 37 are graphical representations of the NHP reproducibility observed in the present study. Despite a central tendency about zero, considerable variation is observed in the difference in HOR/SN values between T1 and T2. An example of this variation in head position is illustrated below. Figure 41 illustrates subject #7 who illustrated significant lowering of the head by 8.5° at the second NHP registration. This is more than two standard deviations from the mean difference.

It is this variation in head position that one must bear in mind when considering the results of NHP reproducibility. While for the majority of subjects, one could expect the reproducibility of NHP to be about 2-3°, for some subjects this might be larger. Previous authors advocated the use of a “natural head orientation” where the operator felt the head position displayed by the subject seemed unnatural [2, 3]. As described by Moorrees [2], subjects may experience “occasional tenseness… resulting in ‘unnatural’ tilting of the head and it was decided… to correct this position, if necessary". In the present study, however, it was decided for the sake of consistency, to not make any such adjustments. This may have implications for the present outcomes as seen in Figure 41.

NOTE: This figure is included on page 111 of the print copy of the thesis held in the University of Adelaide Library.

Figure 41. Comparison of NHP registrations for subject #7 (background T2)

Intra-individual reproducibility of natural head position is typically measured by comparing how the relationship of HOR changes with a stable plane on two or more occasions. In the present study, the assumed stable plane was chosen to be SN. This was unlikely to change over the two month period between T1 and T2 (Section 8.3). With this in mind, the longitudinal records of HOR/SN is effectively a measure of how the reference plane, HOR varies in relationship to SN. The intra-individual reproducibility of NHP compared to true horizontal in the present study was S(i) = 2.08°.

9.5 Clinical Significance

To summarise the main outcomes of the present study, the intra-individual reproducibility of NHP was 2.08° (Dahlberg) while the three intracranial reference planes with the lowest inter-individual variability to HOR were FH, KW line and PM plane (SD 4.63°, 4.67°, and 4.68° respectively). It is evident that the variability of intracranial reference planes in the present investigation are larger than that of the reproducibility of NHP, when both are related HOR. And thus, the hypothesis in Section 6.1 is rejected. There is no craniofacial reference plane with less inter-individual variability than the intra-individual reproducibility of natural head position when both related to true horizontal.

The clinical implications of this are that there were no intracranial reference planes in the present study that could potentially replace NHP and HOR as a gold standard reference plane in cephalometric analysis. The data of the present study therefore support the use of NHP and a true horizontal reference plane in preference to conventional reference planes. This view is shared by many [2, 4, 7, 13, 15] and criticized by few [90].

9.5.1 Clinical Considerations

There are some clinical aspects of cephalometric analysis that may limit the use of NHP in clinical practice.

Lateral head cephalometric analysis is essentially a measure of facial and dental prognathism. Contemporary measures are based on planes such as FH or SN to produce such measures as SNA or SNB. It is obvious, that if two individuals have a different inclination of a reference plane (e.g. SN), then they will potentially have different SNA values despite a remarkably similar facial prognathism. A number of authors have made reference to subjects with the same facial prognathism who illustrate a significant difference of inclination between a chosen reference plane [5, 33, 34] (Figure 8). In other words, an 82° SNA does not indicate the same maxillary prognathism in two or more individuals. In 1975, Jacobson [99] illustrated this point clearly when the “Wits” analysis was suggested as an alternative to the ANB angle (Figure 42).

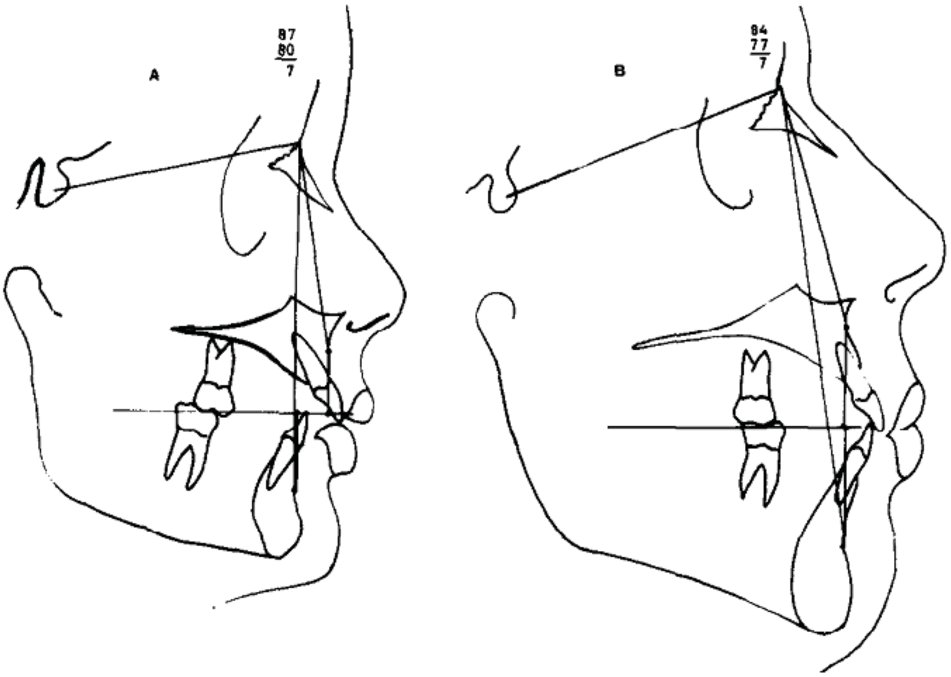


Figure 42. Varied inclination of SN and position of N alter the ANB angle [99]

It is difficult to accurately assess the degree of intra-individual variability of these various craniofacial reference planes because one requires a stable reference to compare them against. Previous investigators have used a true horizontal/vertical plane for this purpose. However, the NHP that allows a true horizontal to be used displays longitudinal intra-individual variability as illustrated above.

Changes in head position will affect the orientation of craniofacial reference planes to HOR and, thus, the validity of measuring such angular variables to HOR this way may be questionable. It is difficult to assess what contribution head position is making to the deviation of the variable from the mean. Intuitively, when visually inspecting the data of the present study (Figure 34), it would seem likely that this contribution is large for outliers who show consistently lower or higher results. This implies that it was largely their head position, and not their craniofacial morphology that contributed to the measured variation in reference plane inclination.

Therefore, it is evident that one of the limitations of NHP in clinical practice is the very feature that validates the use of NHP, and that is its variation. As shown above, the intra-individual variability of NHP to HOR is about 2-3 degrees on average (Table 27). However, on an individual subject basis, this can vary from zero to 8.5° difference between two occasions (Figure 37). A significantly large difference in head position, as seen in subject #7 (Figure 41), is enough to prevent NHP and the true horizontal plane from being useful at all for this individual. This highlights that one must be aware that NHP is a dynamic range of head positions with a normal distribution of reproducibility about zero degrees (Figure 37).

According to the present results in Table 21, approximately 68% of individuals will reproduce NHP within ±3° from zero (1 standard deviation) and 95% of individuals within ±6° from zero (2 standard deviations). To place this concept in perspective a facial profile has been oriented -6°, -3°, 0°, +3°, +6° from the original head position to illustrate the clinical significance of this variability inherent with a mirror guided head position (Figure 43).

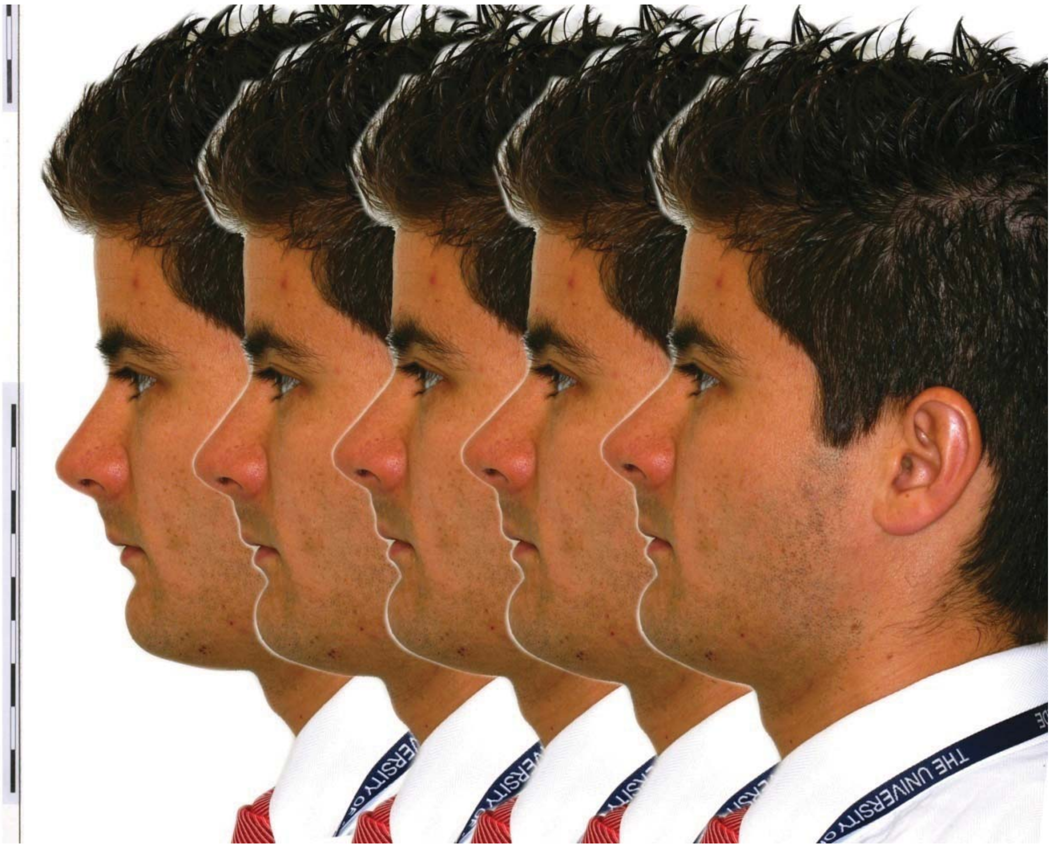


Figure 43. Variation of NHP illustrating 1 and 2 standard deviations

As illustrated in Figure 43, the middle three profiles encompass the range of NHP reproducibility for 2/3 of subjects in the present study. While these differences are small, they are clinically noticeable. Even more so are the remaining 1/3 of subjects who display quite different head registrations between two time points. One could question the validity of using NHP and a HOR reference plane in these subjects. Such a difference renders any measure of facial morphology too variable to be clinically meaningful. After all, the basis of cephalometric analysis is a stable and comparable reference plane/system to determine facial morphology with reliability and accuracy.

9.5.2 Clinical Application of NHP In Cephalometric Analysis

One of the first considerations in cephalometric analysis for orthodontic diagnosis is whether a cephalometric film is required in the first place. Anecdotally, one may argue that for an orthodontic case with mild crowding, pleasing facial profile and minimal growth potential, a lateral cephalometric film is not required and that a lateral head photograph would be a sufficient record of the head from the lateral aspect. This highlights the fact that cephalometric analysis is only one of many tools that are used to form an orthodontic diagnosis.

Should a lateral cephalometric film be deemed necessary, one could argue that treating patients to cephalometric normal values is not valid due to the large variation in skeletal, dental and soft tissue elements in a population sample. This notion was confirmed by Park & Burstone [100] who found that treating to a dentoskeletal standard had questionable validity for producing desirable facial aesthetics or reproducible profiles.

Despite the aforementioned short comings of cephalometric analysis, its diagnostic value would still seem to outweigh these. There are two main uses for cephalometric analysis and NHP.

1. Comparison between individuals (initial orthodontic diagnosis)
2. Comparison of one individual over time (superimpositions)

Inter-individual comparison often forms an integral part of orthodontic diagnosis by measurement of craniofacial morphology of an individual, and comparing these to average values established from various subject samples. The foundation of such analysis is the reference plane against which features of craniofacial morphology are measured. Therefore, it is evident that those reference planes with less inter-individual variability to HOR will produce more meaningful inter-individual comparison. This is the basis of the use of NHP as a craniofacial system in cephalometric analysis.

Comparison of one individual over time allows one to observe treatment or growth changes. Despite some investigators publishing methods of the use of NHP in cephalometric superimposition (Figure 13) [75], it would seem that the results of the present study question the validity of this method. Figure 43 illustrates how the variation of NHP could easily alter the superimposition masking any true changes that may have occurred.

9.6 Future Directions

Conventional 2D radiography has formed the basis of lateral cephalometric analysis since 1931 [1]. While providing valuable diagnostic information, it is not without its shortcomings. It is essentially a 2D representation of a 3D object which often results in superimposition and magnification of paired anatomical structures. Head positioning, film contrast and individual anatomy will often impede simple landmark recognition, rendering this method of craniofacial method more difficult and less accurate.

Cone CT technology developed in the late 1990's has provided the possibility of 3D craniofacial imaging at lower radiation doses compared to conventional CT imaging [101]. From this true 3D representation of craniofacial structures, more accurate and defined reference planes can be defined thereby removing a lot of the error associated with conventional 2D methods. However, if the results of previous 2D NHP studies are considered, the principles of variation of intracranial reference planes may still stand true, regardless of imaging technique. Inter-individual variation of craniofacial morphology and, therefore, reference planes is normal. NHP will more than likely still prove to be useful in 3D imaging.

A significant possibility of 3D imaging is the ability to create new reference planes that have otherwise been previously hard to define or recognise on 2D cephalometric films. Future research in this field of NHP could be based on observing the inter-individual variability of such planes to true vertical or horizontal.

Another aspect of NHP that can be further developed is that of the method of registration. Table 27 highlights that most attempts of a mirror guided NHP registration have resulted in about 2-3° of error. This is to be expected given that head position is a dynamic process of muscular coordination. Attempts should be made to try to reduce this or even seek another method of head positioning. The works of Preston et al [11] compared static NHP with dynamic NHP during walking by means of inclinometer measurements. Although walking head position was about 3° tilted up compared with the static position, they concluded that the dynamic position was no less, perhaps more repeatable than the traditional NHP. Usumez & Orhan followed up this work illustrating very impressive head position reproducibility. Perhaps future research in this field should involve the use of inclinometers and improving their integration into clinical practice.

10. Conclusions

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1. A photographic rig was constructed for consistent and accurate registration of subjects in natural head position. A photographic protocol was developed to record 57 subjects in natural head position.

2. A method of transferring the true vertical line from a lateral head photograph to a lateral head film was developed in the present study. This proved to be reliable with a Dahlberg value of 0.43°.

3. The intra-individual reproducibility of natural head position registrations in the present study was associated with a Dahlberg value of 2.08°. This result is comparable to previous investigations.

4. The investigated craniofacial reference planes displayed larger inter-individual variability than intra-individual NHP reproducibility when both were related to true horizontal. Therefore, the hypothesis in Section 6.1 is rejected. Thus, it was confirmed that a true vertical or horizontal plane from a NHP registration represents a more valid craniofacial reference system.

5. Where it is not possible to use NHP, 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.

11. Appendix

11.1 Consent Forms

For the present study, the University of Adelaide Human Research and Ethics Committee required an appropriate research information sheet to be given to both the subject and subject's parent. Additionally, consent forms were required to be signed by both the subject and subject's parent. These forms were refined a number of times before the Human Research and Ethics Committee approved the present study protocol.

11.1.1 Research Information Sheet

THE UNIVERSITY
OF ADELAIDE
AUSTRALIA

Research Information

Orthodontic department, Faculty of Health Sciences, University of Adelaide, Australia

Study **"A photographic method of recording the head in natural head position"**

Researchers Dr David Madsen, Professor Wayne Sampson (Supervisor)
Orthodontic Dept., Faculty of Dentistry, University of Adelaide

- I would like to invite you to participate in a study. The purposes of this study are to partially fulfil my orthodontic training requirements and design a method of taking side portrait photographs of patients in a head position that represents true life. With this information, the routine side head x-ray can be analysed using this real life "natural head position".

- The potential benefits of this study will be to create a more accurate, and true life representative, way of measuring the jaws and teeth on the side head x-ray. This will potentially result in improved orthodontic treatment planning and monitoring for orthodontic patients in the future.

- As a participant of this study, you will have two side portrait photographs taken while standing up. The first photo is taken today and the second photo will be taken about two months later. The routine side head x-ray that is taken as a part of orthodontic assessment/treatment at the Adelaide Dental Hospital will be also be measured and analysed.

- You will receive no additional x-ray radiation exposure than if you were receiving orthodontic treatment alone. There are no other foreseeable risks, side effects or discomforts anticipated from the two side head portrait photographs.

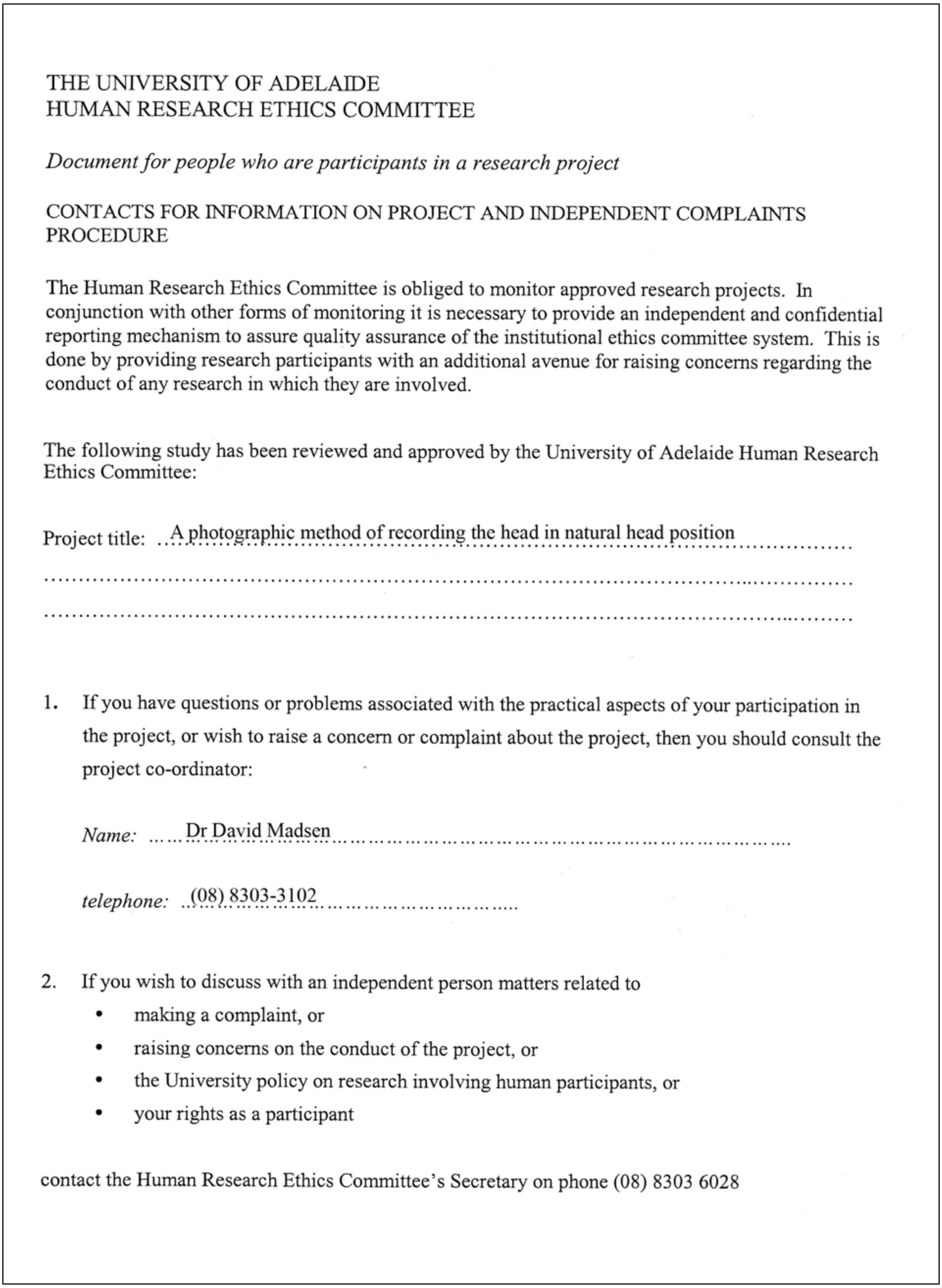
- Participation in this study in voluntary and you have the right to refuse to participate in this study. You may withdraw from this study at any time without prejudice to future treatment at the Adelaide Dental Hospital

- Confidentiality of your details is ensured. Names and contact details will not be published in any results and will remain private at all times. Your side portrait photos may be published in the study thesis, and presented at conferences if you give your consent

- If any problems arise, please contact the research coordinators
  1. Dr David Madsen, Doctor of Clinical Dentistry (Orthodontics) student
     Work Ph (08) 8303-3102 After hours 0431570500
  2. Professor Wayne Sampson, P.R. Begg Chair in Orthodontics, University of Adelaide Work Ph (08) 8303-3293

- If there are any concerns you would like to raise, please contact Dr David Madsen. Please also refer to the attached independent complaints procedure form.

11.1.2 Human Research Ethics Committee Independent Complaints Form



THE UNIVERSITY OF ADELAIDE
HUMAN RESEARCH ETHICS COMMITTEE

Document for people who are participants in a research project

CONTACTS FOR INFORMATION ON PROJECT AND INDEPENDENT COMPLAINTS PROCEDURE

The Human Research Ethics Committee is obliged to monitor approved research projects. In conjunction with other forms of monitoring it is necessary to provide an independent and confidential reporting mechanism to assure quality assurance of the institutional ethics committee system. This is done by providing research participants with an additional avenue for raising concerns regarding the conduct of any research in which they are involved.

The following study has been reviewed and approved by the University of Adelaide Human Research Ethics Committee:

Project title: A photographic method of recording the head in natural head position

1. If you have questions or problems associated with the practical aspects of your participation in the project, or wish to raise a concern or complaint about the project, then you should consult the project co-ordinator:

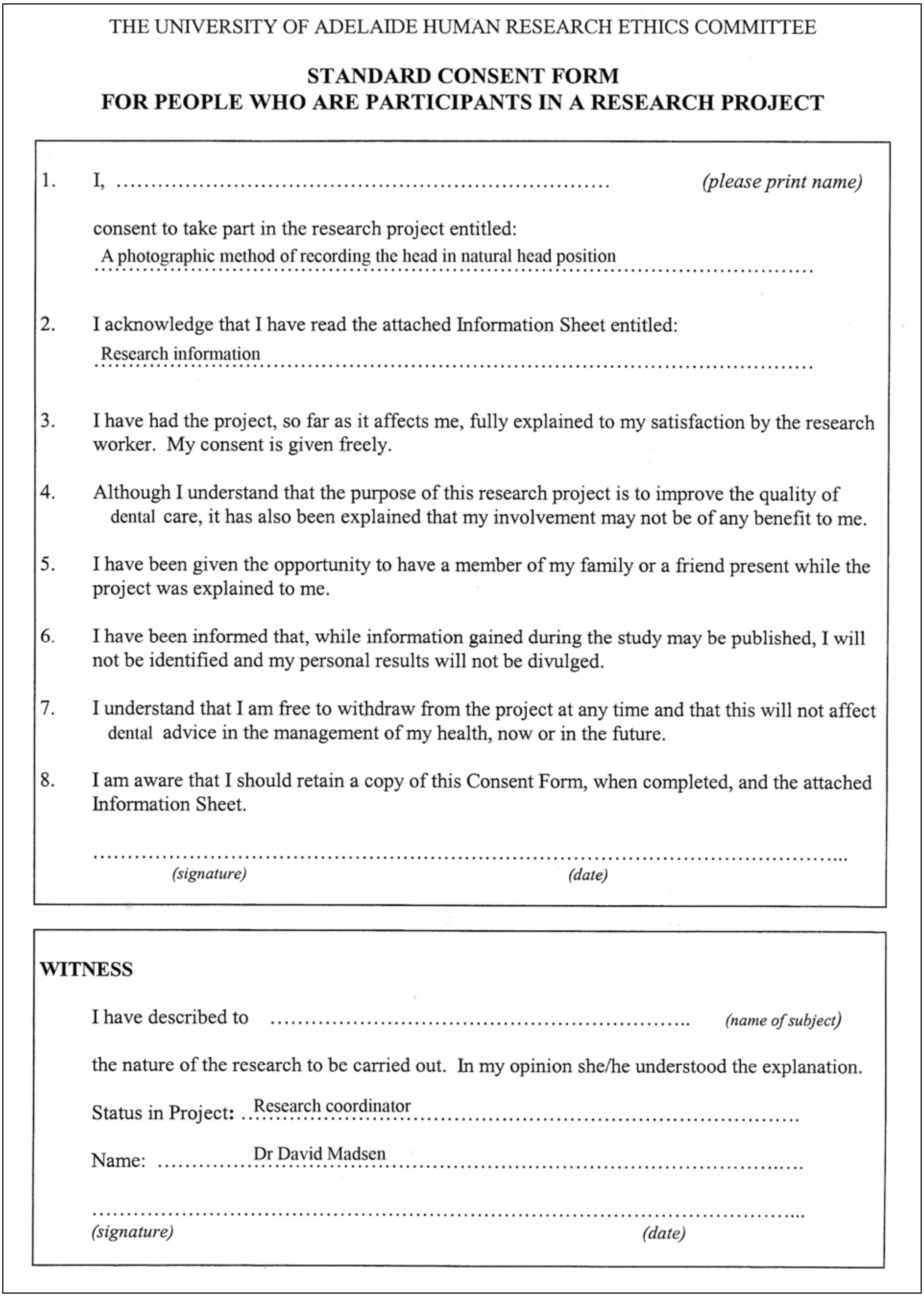
   Name: Dr David Madsen

   telephone: (08) 8303-3102

2. If you wish to discuss with an independent person matters related to
   - making a complaint, or
   - raising concerns on the conduct of the project, or
   - the University policy on research involving human participants, or
   - your rights as a participant

contact the Human Research Ethics Committee's Secretary on phone (08) 8303 6028

11.1.3 Child Consent Form



THE UNIVERSITY OF ADELAIDE HUMAN RESEARCH ETHICS COMMITTEE

STANDARD CONSENT FORM
FOR PEOPLE WHO ARE PARTICIPANTS IN A RESEARCH PROJECT

1. I, ………………………………………………………… *(please print name)*

   consent to take part in the research project entitled:
   A photographic method of recording the head in natural head position ……………………………

2. I acknowledge that I have read the attached Information Sheet entitled:
   Research information ……………………………………………………………

3. I have had the project, so far as it affects me, fully explained to my satisfaction by the research worker. My consent is given freely.

4. Although I understand that the purpose of this research project is to improve the quality of dental care, it has also been explained that my involvement may not be of any benefit to me.

5. I have been given the opportunity to have a member of my family or a friend present while the project was explained to me.

6. I have been informed that, while information gained during the study may be published, I will not be identified and my personal results will not be divulged.

7. I understand that I am free to withdraw from the project at any time and that this will not affect dental advice in the management of my health, now or in the future.

8. I am aware that I should retain a copy of this Consent Form, when completed, and the attached Information Sheet.

………………………………………………………………………………
(signature) *(date)*

WITNESS

I have described to ………………………………………………… *(name of subject)*

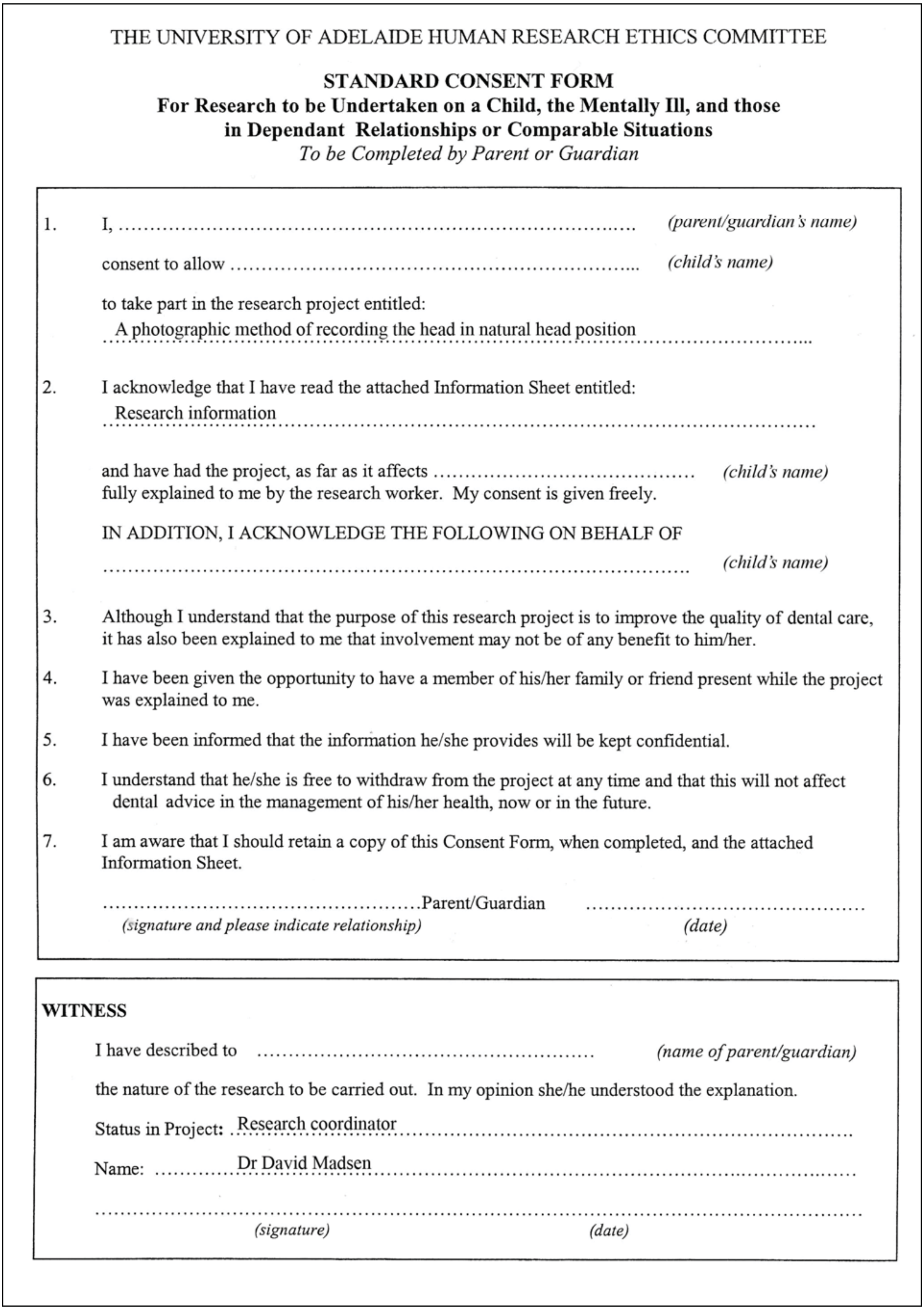
the nature of the research to be carried out. In my opinion she/he understood the explanation.

Status in Project: Research coordinator ……………………………………

Name: Dr David Madsen ……………………………………………

………………………………………………………………………………
(signature) *(date)*

11.1.4 Adult Consent Form



THE UNIVERSITY OF ADELAIDE HUMAN RESEARCH ETHICS COMMITTEE

STANDARD CONSENT FORM
For Research to be Undertaken on a Child, the Mentally Ill, and those in Dependant Relationships or Comparable Situations
To be Completed by Parent or Guardian

1. I, ………………………………………………………… *(parent/guardian's name)*

   consent to allow ……………………………………………… *(child's name)*

   to take part in the research project entitled:
   A photographic method of recording the head in natural head position

2. I acknowledge that I have read the attached Information Sheet entitled:
   Research information

   and have had the project, as far as it affects …………………………… *(child's name)*
   fully explained to me by the research worker. My consent is given freely.

   IN ADDITION, I ACKNOWLEDGE THE FOLLOWING ON BEHALF OF
   ……………………………………………………………… *(child's name)*

3. Although I understand that the purpose of this research project is to improve the quality of dental care, it has also been explained to me that involvement may not be of any benefit to him/her.
4. I have been given the opportunity to have a member of his/her family or friend present while the project was explained to me.
5. I have been informed that the information he/she provides will be kept confidential.
6. I understand that he/she is free to withdraw from the project at any time and that this will not affect dental advice in the management of his/her health, now or in the future.
7. I am aware that I should retain a copy of this Consent Form, when completed, and the attached Information Sheet.

…………………………………Parent/Guardian ……………………………
(signature and please indicate relationship) *(date)*

WITNESS

I have described to ……………………………………… *(name of parent/guardian)*

the nature of the research to be carried out. In my opinion she/he understood the explanation.

Status in Project: Research coordinator

Name: Dr David Madsen

……………………………………………………………………………
(signature) *(date)*

11.2 Definitions

11.2.1 Cephalometric Landmark Definitions

Where bilateral structures where not superimposed, the average of the two points was taken.

1. **Anterior nasal spine (ANS)** - The tip of the median, sharp bony process of the maxilla at the lower margin of the anterior nasal opening [102]

2. **Anterior tubercle (At)** - The point on the tip of the anterior surface of the anterior tubercle of the first cervical vertebra.

3. **Articulare (Ar)** - The point of intersection of the inferior cranial base surface and the averaged posterior surfaces of the mandibular condyles [102]

4. **Basion (Ba)** - The most inferior, posterior point on the anterior margin of foramen magnum [102]

5. **cv2ap** – The apex of the odontoid process of the second cervical vertebra [58]

6. **Ethmoid registration point (SE)** - Intersection of the anterior cranial floor (superior surface) with the averaged greater sphenoid wing [102].

7. **Gonion (Go)** – The point a tangent line from menton makes with the inferior surface of the ramus of the mandible. In cases where a tangential line could not be easily constructed (i.e. low gonial angle and absence of antegonial notch), gonion was placed at the inferior surface of the ramus half way between the anterior and posterior borders of the ramus.

8. **Maxillon (Max)** – A point just below (occasionally above) the zygomatic key ridge, midway between the upper and lower border of the palate [18]

9. **Menton (Me)** - The most inferior point on the mandibular symphyseal outline [102]

10. **Nasion (N)** - The junction of the frontonasal suture at the most posterior point on the curve at the bridge of the nose [102]

11. **Occipitale (Occ)** – The lowest point on the occipital bone. [18]

12. **Opisthion (Op)** - The posterior midsagittal point on the posterior margin of foramen magnum [102]

13. **Orbital margin point (OM)** - The superoinferior midpoint between the lower and upper orbital rims [31]

14. **Orbitale (Or)** - The lowest point on the average of the right and left borders of the bony orbit [102]

15. **PM point (PM)** - The average midline point of the anterior-most point on the lamina of each greater wing of the sphenoid [31]

16. **Porion (Po)** - A point on the superior edge of the auditory canal.

17. **Posterior tubercle (Pt)** - The point on the tip of the posterior surface of the posterior tubercle of the first cervical vertebra.

18. **Posterior nasal spine (PNS)** - The most posterior point at the sagittal plane on the bony hard palate [102]

19. **Pterygomaxillare (Ptm)** - The average most posteroinferior point on the maxillary tuberosities [31]

20. **Pterygomaxillary fissure, inferior (PTM)** - The most inferior point on the average of the right and left outlines of the pterygo-maxillary fissure [102]

21. **Sella (S)** - The centre of the pituitary fossa [102]

22. **Sella tangent (St)** - Consider a line passing through nasion and tangent to the inferior border of sella. St is the point at which this line touches the inferior border of sella [103]

23. **Superior orbital margin (SOr)** – Taken as the anterior and superior most point on the superior orbital margin

24. **Tuberculum sellae inferior (Ti)** - A point on the anterior wall of sella turcica approximately 2mm inferior to tuberculum sellae [94]. This point was used by Barbera et al [94] as an estimated substitute for the posterior landmark to used to construct the NHA plane (Section 11.2.2 #8) which is normally the orbital axis point – the supero-inferior midpoint between the superior orbital fissures and the inferior rims of the optic canals [31]. This point was developed from a landmark verification process outlined in Section 7.7.1.

11.2.2 Cephalometric Plane Definitions

Where bilateral structures where not superimposed, the average of the two points was taken.

1. **Anterior tubercle-Posterior tubercle (AtPt)** - At-Pt

2. **Foramen magnum line (FML)** - Ba-Op

3. **Frankfort Horizontal Plane (FH)** - Po-Or

4. **Functional Occlusal Plane (FOP)** - line of best fit between the occlusal surfaces of the upper and lower first premolars to second molars.

5. **Krogman-Walker line (KW line)** - Occ–Max [18]

6. **Mandibular plane (Md Plane)** - Me-Go. In cases where no well defined antegonial notch could be found at the inferior surface of the mandibular body, Go was assigned to a point on the inferior margin of the mandible between the anterior and posterior borders of the ramus.

7. **Neutral Horizontal Axis (NHA)** - OM–Ti. Described by McCarthy & Lieberman as a line passing through the inferior border of the optic canal [31]. It is defined as passing through orbital margin point (OM – superoinferior midpoint between the superior and inferior orbital rims) and orbital axis point (OA – superoinferior midpoint between the superior orbital fissures and the inferior rims of the optic canals) [29, 31].

8. **Palatal plane (P plane)** - ANS-PNS

9. **Posterior maxillary plane (PM plane)** - PM-Ptm [30]

10. **Posterior nasomaxilla vertical (PM vertical)** - SE-PTM [28].

11. **Sella-Nasion (SN)** - S-N

12. **Sella tangent-Nasion (StN)** – St-N [103]

13. **True horizontal line (HOR)** – This was taken as a pure perpendicular plane to the true vertical plumb line recorded in the lateral head photograph. This was drawn through Ar.

11.3 Formulas and Calculations

11.3.1 Power Test Calculations

Power test formula [104, 105]

$$Power = 1 - \beta = 1 - P(typeIIerror)$$

$$\beta \approx P\left[N(0,1) < -Z_{1-\alpha/2} + \frac{|\mu_1 - \mu_0|}{\sigma / \sqrt{n}} \right]$$

where β is the probability of committing a type II error, μ_1-μ_0 is an arbitrarily selected clinically significant change (2° for all power tests), σ is the standard deviation, n is the sample size, Z is the z value, α is the significance level (0.05 for all power tests).

Alternatively to determine the sample size [104, 105],

$$n = \frac{\sigma^2 (Z_{1-\alpha/2} + Z_{1-\beta})^2}{(\mu_1 - \mu_0)^2}$$

where n is the sample size, σ is the standard deviation, Z is the z value, α is the significance level, β is the probability of committing a type II error, and μ_1-μ_0 is an arbitrarily selected clinically significant change.

- Sample size estimation

  The power of n=55 subjects is 0.80 to detect a change of 2°.

$$Power = 1 - \beta = 1 - P(typeIIerror)$$

$$\beta \approx P\left[N(0,1) < -Z_{1-\alpha/2} + \frac{|\mu_1 - \mu_0|}{\sigma / \sqrt{n}} \right] = P\left[N(0,1) < -1.96 + \frac{|2|}{5.3 / \sqrt{55}} \right]$$

$$= P(Z < 0.84) = 0.5 - 0.30 = 0.20$$

$$\therefore Power = 1 - 0.20 = 0.80$$

The number of subjects required to achieve a power of 0.90 is 91.3 subjects

$$n = \frac{\sigma^2 (Z_{1-\alpha/2} + Z_{1-\beta})^2}{(\mu_1 - \mu_0)^2} = \frac{5.3^2 (1.96 + 1.645)^2}{(2)^2} = 91.3$$

The number of subjects required to achieve a power of 0.80 is 55 subjects

$$n = \frac{\sigma^2 (Z_{1-\alpha/2} + Z_{1-\beta})^2}{(\mu_1 - \mu_0)^2} = \frac{5.3^2 (1.96 + 0.842)^2}{(2)^2} = 55.1$$

- Variance of craniofacial reference planes

  The power of the present study to determine the variance of craniofacial reference planes was 0.82.

$$Power = 1 - \beta = 1 - P(typeIIerror)$$

$$\beta \approx P\left[N(0,1) < -Z_{1-\alpha/2} + \frac{|\mu_1 - \mu_0|}{\sigma/\sqrt{n}} \right] = P\left[N(0,1) < -1.96 + \frac{|2|}{5.3/\sqrt{57}} \right]$$

$$= P(Z < 0.89) = 0.5 - 0.3233 = 0.18$$

$$\therefore Power = 1 - 0.18 = 0.82$$

- Reproducibility of NHP

  The power of the present study to determine the reproducibility of NHP was 0.99.

$$Power = 1 - \beta = 1 - P(typeIIerror)$$

$$\beta \approx P\left[N(0,1) < -Z_{1-\alpha/2} + \frac{|\mu_1 - \mu_0|}{\sigma/\sqrt{n}} \right] = P\left[N(0,1) < -1.96 + \frac{|2|}{3/\sqrt{39}} \right]$$

$$= P(Z < 2.20) = 0.5 - 0.4861 = 0.01$$

$$\therefore Power = 1 - 0.01 = 0.99$$

11.3.2 Cephalometric Software Validation

Angular measurements

- AC-BE

  $\tan\theta = \frac{y}{x}$ where *x* and *y* are two sides of a triangle forming a right angle, and θ is the angle opposite *y*.

$$\theta = \tan^{-1}\frac{y}{x} = \tan^{-1}\frac{1}{2} = 63.43^\circ$$

- AC-DF

  Angle BAC = 26.57°

  Angle AC-DF = 45° - 26.57° = 18.43°

Linear measurement

- AE

  Pythagoras's Theorem

$x^2 = y^2 + z^2$ where *x* is the hypotenuse of a right angled triangle, *y* and *z* and the two sides adjacent the right angle. And therefore,

$x = \sqrt{y^2 + z^2}$ where the two sides adjacent the right angle are known.

$= \sqrt{3^2 + 1^2} = 3.16$

11.3.3 Descriptive Statistics

- **Mean**

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Where $\bar{x}$ is the mean, *n* is the sample and

$\sum_{i=1}^{n} x_i$ is the sum of all values $x_1 + x_2 + \ldots + x_n$

- **Standard deviation (SD)**

$$s = \sqrt{\frac{1}{n-1}\left(\sum x_i^2 - \left(\sum x_i\right)^2 / n\right)}$$

Where $\sum x_i^2$ is the sum of each observation squared,

$\left(\sum x_i^2\right)$ is the square of the sum of all observations, and *n* is the sample size

- **Range (Min, Max)**

This is simply the difference between the largest and smallest value for each variable.

- **Coefficient of variation (CV)**

CV=$\left(s / \bar{x}\right)100$

Where *s* is the standard deviation and $\bar{x}$ is the mean

11.3.4 Method Error

- **Mean diff**

mean of differences between paired values from the two determinations

- **SD diff**

  standard deviation of paired differences between the two determinations

- ***t*-test**

  value of *t* as derived from Student's *t*-test (described below)

  To determine systematic error, the use of paired *t*-tests between the two measurements in the error study allowed the determination of any significant differences (at $p<0.05$ level)

  The *t* value was calculated as:

  $$t = \frac{Mean\,diff}{SD\,diff / \sqrt{n}}$$

- ***p* value**

  The statistical association between two means (Mean diff)

- **S(i)**

  Dahlberg statistic

  To determine the magnitude of the random error of landmark location the Dahlberg statistic [106] was calculated as:

  $$S(i) = \sqrt{\frac{\sum diff^2}{2n}}$$ where n = number of double determinations

- **E(var)**

  Error variance; the variance due to measurement error expressed as a percentage of the total observed variance.

  $$E(var) = \frac{S(i)^2}{S_{obs}^{\ 2}}$$ x 100 (i.e.. expressed as a percentage)

  Where:

  $S(i)^2$ = variance due to measurement error, based on the Dahlberg statistic, S(i)

  And S_{obs}^2 = observed variance of sample as determined by calculating the average of the original T1 values for the total sample (i.e. observed SD of variable at T1, squared). This value would include true sample variance and variance due to measurement error.

- **Reliability**

  Reliability = 100 – E(var) (i.e.. expressed as a percentage)

  Reliability coefficients greater than 90% were considered to be acceptable while values less than 80% rendered the measurement doubtful.

12. References

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