Reproducibility of Natural Head Position assessed with stereophotogrammetry

Short title: NHP assessed with stereophotogrammetry

Gundega Jakobsone [a]

Ville Vuollo [b]

Pertti Pirttiniemi [c]

[a] Associated Professor, Department of Orthodontics, Riga Stradins University, Riga, Latvia

[b] Researcher, Research Unit of Oral Health Sciences, Faculty of Medicine, University of Oulu, Oulu, Finland; Medical Research Center, Oulu University, Hospital and University of Oulu, Oulu, Finland

[c] Professor, Research Unit of Oral Health Sciences, Faculty of Medicine, University of Oulu, Oulu, Finland; Medical Research Center, Oulu University Hospital and University of Oulu, Oulu, Finland

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DR GUNDEGA JAKOBSONE (Orcid ID : 0000-0003-0509-1709)

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Corresponding author mail-id: g.jakobsone@latnet.lv

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Abstract

Objective. The aim of this study was to assess the stability of Natural Head Position (NHP) over time using the 3dMDface System.

Setting and sample population. This was an experimental study. Three-dimensional facial images of 40 students were captured on two different occasions, with an interval of at least two weeks.

Materials and Methods. The images were taken using a stereophotogrammetric device (3dMD, Atlanta, Georgia). The mirror positioned NHP was obtained in a standing position and then replicated in a sitting position for capturing. The self – balanced NHP was taken in a sitting position. Rapidform 3D software was used for position angle calculations. The angle changes between the positions were calculated for rotations around the x-, y- and z- axes.

Results. The differences between NHP in the self-balanced and mirror positions recorded on the first and second occasions were 2.43 and 1.75 degrees, respectively, around the x-axis. The average changes in NHP around the x-axis between the self-balanced and mirror balanced positions exceeded 3 degrees at the two-week interval. The differences were smaller for the

rotations around the y- and z- axes. Some subjects consistently tended to hold their heads in a more extended position when self-balanced, while others did this when mirror balanced. There was no difference in the reproducibility of NHP between men and women.

Conclusion. The reproducibility of NHP for consecutive stereophotogrammetric captures is generally acceptable. The reproducibility of NHP using the mirror position was slightly better compared with NHP in the sitting self-balanced position.

Keywords: 3D imaging, Head, Natural Head Position

Introduction

For several decades, Natural Head Position (NHP) has been proposed for use in orthodontic practice and research. It has been widely investigated with two-dimensional images in orthodontic patients and students.[1-3] Usually, lateral cephalograms have been used to describe NHP in the sagittal plane,[1-3] while anteroposterior cephalograms have been used to assess NHP in the frontal plane.[4] It has been shown that individuals are able to reproduce NHP in the range between 1.5 to 2.5 degrees to the true vertical line in the sagittal plane.[1-3] The average difference between two repeated measurements of NHP to the true vertical line in the frontal plane has been shown to be about one degree.[4]

As three-dimensional (3D) imaging techniques have become more common in different fields of orthodontics, interest in the 3D assessment of NHP has increased, especially in the field of orthognathic surgery.[5-10] However, because of the radiation issue, it is impossible to conduct a study into the reproducibility of NHP in 3D using computed tomography. Several methods for re-establishment of NHP prior to orthognathic treatment planning have been proposed and significant differences among them have been found.[11] Cevidanes et al.[12] have attempted to assess NHP on cone-beam computed tomography images by simulating NHP and comparing that with the intracranial reference planes. This method, known as Natural Head Orientation, has been validated but largely relies on the experience of the assessor and is considered to be subjective.[13] 3D photography could offer a possibility to assess reproducibility of NHP without exposing subjects to radiation. Additionally, some authors have suggested that 3D face-scanning methods could replace the cranial reference landmarks to reduce the field of view (FOV) of Cone

Beam Computed tomography (CBCT) scans[14] or to cut down the application of lateral cephalograms.[15]

Although several methods have been proposed to record NHP in 3D,[11] only one study[16] has reported on the stability of NHP in all three dimensions. Additionally, one study has reported the stability of NHP for rotations around the x - and z- axes.[17]

Aim of the study: To assess the stability of Natural Head Position in repeated measurements by means of stereophotogrammetry. The null hypothesis: there is no difference in NHP recorded by different methods on the same day or over a time interval.

Materials and methods

This was an experimental study using dental students as a cohort. The permission to conduct the study was obtained from the Committee of Ethics at Rīga Stradiņš University, Latvia. In the study, all last year dental students who agreed to participate in the study were included. Informed consent was obtained from all the participants. No exclusion criteria were applied. The study sample consisted of 21 male students and 20 female students (mean age 25.5 ± 1.6). All the subjects were recorded twice using the stereophotogrammetry-based 3dMDface System (3dMD, Atlanta, GA, USA) in two sessions, with an interval of at least two weeks between the sessions. One of the students did not show up for the second capture and was excluded from the study.
A sample size for this study was calculated. The rotation around the x-axis was set as the primary outcome value. A clinically relevant value of 2 degrees with a standard deviation of 3 degrees was assumed. According to the calculated sample size, at least 20 subjects were necessary to retrieve $\beta = 0.80$ with α set at 0.05 when using the One Sample T-Test and Paired T-Test.
First, a pivot-mounted fluid-level device[3,18] was attached to the subject's temple with double-sided tape. NHP for all participants was established and recorded using a mirror as described by Solow and Tallgren.[1] Each subject performed a series of neck bending exercises and, while looking into their eyes, walked to a position one metre away from a 20 × 100 mm wall-mounted mirror; the fluid-level device was adjusted horizontally. The standing mirror position (MP) was then replicated in the sitting position. The subjects were seated at the same marked position according to the equipment calibration procedure. The seat had adjustable height, and the height

of the seat was adjusted according to the mesh provided by the machine settings prior each set of the imaging of the same subject. Small adjustments of the head position to align the fluid level were made if necessary. No other adjustments of the head position were performed. After ten minutes, the fluid-level device was removed, and the second capture was taken in a seated position when the subjects were asked to relax and position the head according to their own feeling of NHP. This scan would represent the self-balanced position (SBP) according to Sollow and Tallgren[1] (Figure 1). During the capture of 3D images, subjects were asked to bite in maximum intercuspation, swallow, relax their lips, and keep their eyes open. All images were recorded by the same photographer. Two sets of two images, taken with an interval of at least two weeks, were obtained using the same procedure.

The following comparisons were made:

- Difference between the facial 3D models in the SBP and MP taken on the same day were measured.
- The two models in both the SBP and MP, with at least a two-week interval, were compared separately. These comparisons would determine the reproducibility of NHP assessed with the same method.

The facial surfaces were cut, leaving out distinct parts such as the hair and neck, with 3dMDpatient v2.0 (3DMDpatient™ Software Platform, 3dMD Ltd, Atlanta, USA) by one of the researchers (G.J.) and sent to the other researcher (V.V.) who was not aware of the performance of each subject involved in the experiment. Comparable surfaces were superimposed in a semiautomatic way using the iterative closest point (ICP) algorithm so that the position of the object did not rotate. Then, superimposition was performed again for the translated surfaces so that the rotation was allowed. There might be some translation with the second superimposition because the ICP was not optimized only for translation. Thus, the ICP ignoring the rotation was iterated so many times that the translation in the basic ICP registration would be below 0.1 mm in each of the axes. When this condition was met, the images were superimposed with both the translation and the rotation allowed. The transformation matrix of the final superimposition showed the rotational difference of surfaces in rotations around the x-axis (pitch rotation), y-axis (yaw rotation) and z-axis (roll rotation). The superimpositions and the rotation angle calculations

were done with Rapidform 2006 software (Geomagic, Rock Hill, SC, USA), and the processes were automated with a set of in-house Visual Basic for Applications (VBA) subroutines developed for Rapidform.

No accuracy test for the ICP procedure was performed, because the ICP is a deterministic algorithm that minimizes the difference between two clouds of points. With the same input, it will always produce the same output.

Statistical analysis

Statistical software IBM SPSS, 23.0 (SPSS Inc., Chicago, Illinois, USA) was used for statistical analysis. The data was tested for normality of distribution using the Shapiro-Wilk test. The One Sample T-Test was used to assess whether the angle between the positions of the two facial models was more than 2. A Paired T-Test was used to assess the differences between the two images obtained either with two different methods or at two different time points.

Results

There were no gender differences in NHP, except that the men tended to tilt their heads more to the left in the SBP compared to the MP during the second capturing (- 1.30 degrees, CI -2.01 to -0.55, $p = 0.001$). Therefore, the data were pooled together for further analysis.

The angle means were significantly larger than two degrees for the self-balanced NHP taken in a 2-week interval for the x-axis ($p = 0.001$) and for the y-axis ($p = 0.041$) as well as for the mirror positioned NHP in a 2-week interval for the x-axis ($p = 0.005$). NHP taken with either of the methods on the same day did not show any statistically significant results (Table 1). Some individuals had clinically significant rotations, and they were most often observed in the x-axis, followed by the y-axis (Table 2). Only 10% of individuals had differences between the scans of more than four degrees around the x-axis for the images taken on the same day with different methods, while about one-third had a difference of more than four degrees when the images were taken with the two-week interval.

The highest difference in NHP between the SBP and MP was recorded in the rotation around the x-axis during the first capturing session (0.68 ± 3.64 degrees), and there was significant variation ranging from 12.41 to 13.68 degrees (Table 3). The SBP showed lower reproducibility compared

with the MP, but the difference was not clinically significant. NHP around the x-axis was more stable in the MP (0.88 ± 4.05) compared to the SBP (1.73 ± 3.69), but the difference was not statistically significant (Table 4). The differences between the SBP and MP for other rotations were insignificant.

Discussion

The 3dMDface system has a verified ability to consistently record geometric accuracy of <0.2 mm root mean square (RMS). It is not, however, possible to have identical facial expressions in two consecutive capturing sessions. Vuollo et al. demonstrated good reproducibility for facial expressions.[19] In the present article, the ICP algorithm was used for superimposition, and the angles were calculated automatically. Superimposition was done so that 3D models did not rotate. Therefore, the location of facial surface was insignificant in the respect of origin while doing angle calculations. Independent examiners were involved in each step of the study. The photographer captured the images according to a protocol, and no additional efforts were taken to correct NHP of subjects. The images were taken while subjects were seated. It has previously been shown that differences in NHP in the sitting and standing positions were negligible if the fluid-level device was used.[3] The sitting position would better represent the clinical positioning of the 3D imaging equipment. In the present study, the fluid-level device was used to transfer the rotation around the x-axis from the mirror position into the camera setting where the patients were sitting without any reference to the mirror. The pivot device was used only for recoding NHP in the MP around the x-axis because it was previously validated only for assessment of the rotations around the x-axis.[3,18] The use of the mirror was found to be misleading for recording NHP in the frontal plane.[4] Because the rotations around the y- and z- axes were not corrected by any device, they could be considered as self-balanced in all recordings. However, the rotations around the y-axis may be influenced by an operator's instructions while positioning the subject in front of the camera.

There were no statistically significant differences between genders for NHP except the small difference of the rotation around the z-axis in the second capturing session. This corresponds to all previous findings on cephalograms[2,17,20,21] and the study performed with stereophotogrammetry; however, the rotation around the y-axis was not assessed in that study.[17]

Most of the previous studies reporting on the reproducibility of NHP used statistical calculations.[1,3,4,17] In the present study, direct superimposition of the 3D images was used. The angles between the images were measured in the three perpendicular planes. If a subject was able to reproduce NHP in two recordings, the difference would have been 0. A clinically significant difference of 2 degrees was set as a test value. There were small but statistically significant differences between the superimposed images, indicating some inconsistency in the reproducibility of NHP. The differences in NHP were higher over time (Table 1), regardless of the method used to record the head position (Table 4). This finding supports the previous reports.[2,16]

The previous experimental radiological studies were limited in the number of captures due to radiation issues. It is difficult to compare the present study with the cephalometric studies. However, some approximations can be made. Solow and Tallgren[1] reported a 2.48-degree difference between repeated cephalograms in the SBP. Our finding of a 3.26-degree difference between the two scans taken in the SPB was slightly higher. The finding of the present study that NHP in the MP has higher repeatability compared with the SBP is in line with other studies.[1,2,17] In general, the subjects tended to keep their heads more extended in the MP, which corresponds with other studies.[1,2,18] However, the average difference was smaller (0.86 degrees) in the present study. It has to be noted that some subjects held their heads more upright in the MP in our sample, while some subjects held their heads more upright in the SBP (Table 3); for each subject, their specific tendency was maintained throughout both capturing sessions.

It is not possible to isolate the rotations in the lateral cephalograms. Therefore, several research groups developed new methods for recording NHP in 3D. Xia et al. used orientation sensors with electronic devices that were auto-calibrated, aligned and embedded in a box for mounting on a bite jig.[7] The orientation information was automatically recorded and transferred to the final 3D model of the device frame. However, this approach had several drawbacks: surface registration of the box chassis to the captured faces 3D models and adverse effects on NHP when holding the box. Recently, Hsung et al. described a simple method for recording 3D reference lines for assessment of NHP based on a specially designed reference board.[22] They reported high reliability for placement of this board.[22]

Two other studies used markers[16] or laser lines and the DWRuler[17] to record the reference planes before taking the 3D photographs. Placing ink dots on the face or adjusting the ruler could have

introduced additional sources of error. These studies reported good reproducibility of NHP by comparing the angles of the reference lines. The best reproducibility was found for the rotations around the z-axis, followed by the y-and x-axes.[16,17] The results of the present study are consistent with those findings; however, the absolute values were higher in the present study. Position of the head depends on stimulus from the vestibular system coordinated with the visual input and strength of the supporting muscles.[23] For daily activities, humans are more prone to adopt their head positions in the sagittal plane. This would explain the consistent finding of the poorer reproducibility of NHP in the x-axis for healthy young individuals.

As the results of our study indicate that NHP in the sagittal plane is the least reproducible, it is recommended that NHP in the sagittal plane be obtained according to the standard procedure[1], and that data should be recorded before scanning patients with CBCT for orthognathic treatment planning purposes, as was first proposed by Damstra et al.[5] and later adopted by Bobek et al.[6]

Lately, the handheld scanners are gaining popularity due to their price and undemanding use. The facial scans can be obtained with these scanners in any position with or without the subjects looking in the mirror. Scanning seated subjects without any reference would produce a greater variability of NHP.

Conclusions

The average consistency of NHP in the self-balanced position and mirror position was good, with clinically insignificant rotations of less than three degrees for most subjects. However, one-third of individuals may have rotations of the head around the x-axis of more than four degrees. NHP in the standing position using the mirror as a reference was more consistent. In general, NHP was more consistent if taken on the same day by two different methods rather than if taken on two consecutive occasions using the same method.

Figure 1. The facial images taken in the mirror balanced NHP with the pivot-mounted fluid-level device on the left side and in the self-balanced position NHP on the right side.

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Table 1. The differences in degrees between the two images captured in the mirror position (MP) and self-balanced position (SBP) on the same occasion or in the same position on the 2 different occasions

Rotations	SBP vs. MP T1			SBP vs. MP T2			MP T1T2			SBP T1T2		
	Mean diff.	SD	P value	Mean diff.	SD	P value	Mean diff.	SD	P value	Mean diff.	SD	P value
Pitch (X – axis)	2.43	2.77	0.168	1.75	1.38	0.867	3.14	2.66	0.005	3.26	2.41	0.001
Yaw (Y – axis)	1.42	1.20	0.998	1.22	1.12	1.000	2.00	1.72	0.486	2.53	1.89	0.041
Roll (Z-axis)	1.22	1.04	1.000	0.93	0.92	1.000	1.48	0.98	0.999	1.47	1.14	0.997

One sample T-test to test the difference of the mean value from 0.

Table 2. Number of individuals with the differences between the two images more than 2 degrees and more than 4 degrees

Rotations	SBP vs. MP T1			SBP vs. MP T2			MP T1T2			SBP T1T2		
	Dif. < 2	2<Dif.<4	Dif. > 4	Dif. < 2	2<Dif.<4	Dif. > 4	Dif. < 2	2<Dif.<4	Dif. > 4	Dif. < 2	2<Dif.<4	Dif. > 4
Pitch (X – axis)	22	14	4	26	10	4	19	9	12	16	10	14
Yaw (Y– axis)	28	11	1	29	10	1	23	14	3	18	15	7
Roll (Z-axis)	34	5	1	35	5	0	28	12	0	32	6	2

MP – mirror position, SBP – self – balanced position.

Table 3. Mean differences (degrees) in the rotations around x, y, and z-axis between the mirror positions and self-balanced positions for the 2 timepoints

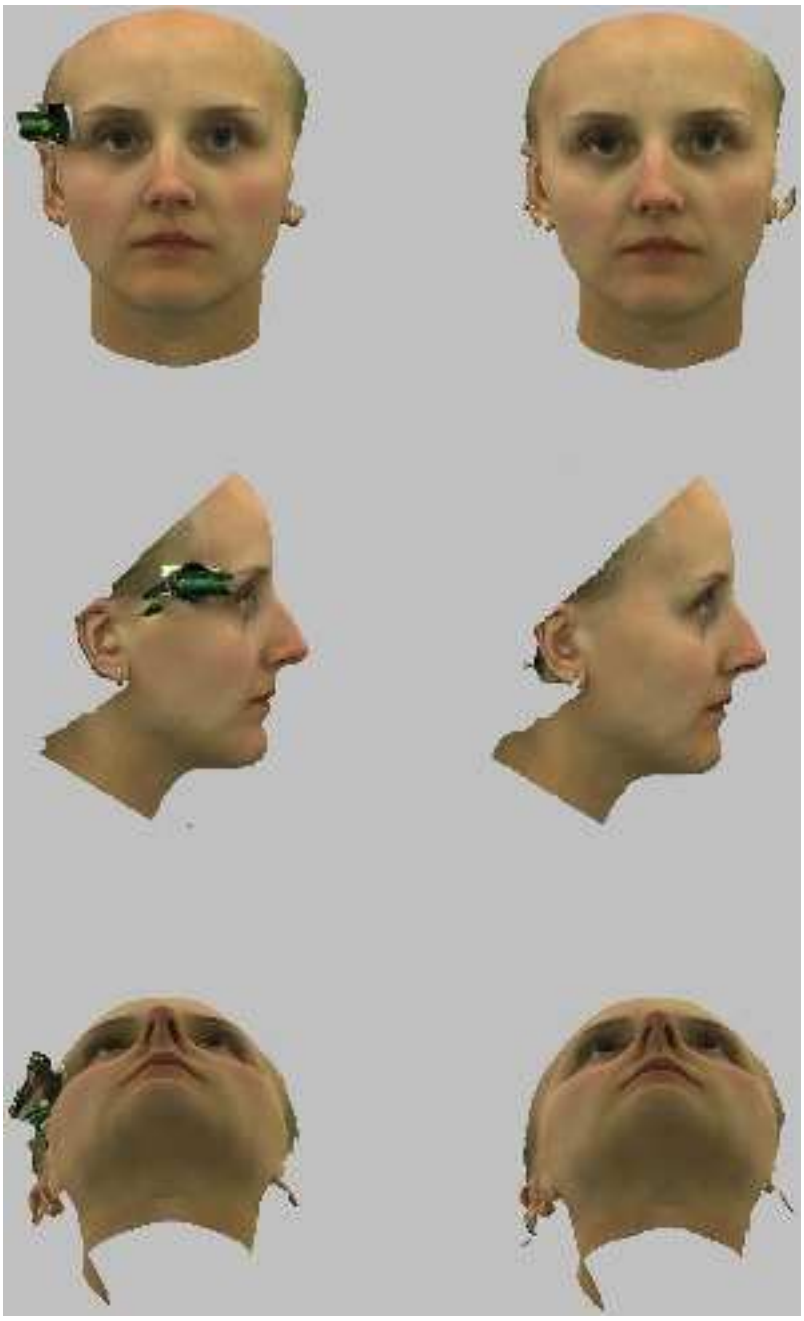
Rotations	SBP vs. MP T1			SBP vs. MP T2			SBP vs. MP T1T2			
	Mean	SD	Range	Mean	SD	Range	Diff.	95% CI		P value
								lower	upper	
Pitch (X – axis)	0.68	3.64	- 12.41 – 13.68	- 0.18	2.24	- 5.13 – 4.07	0.86	- 0.58	2.30	0.233
Yaw (Y – axis)	-0.10	1.87	- 4.47 – 3.13	0.03	1.66	- 4.13 – 3.28	- 0.13	- 0.83	0.58	0.715
Roll (Z-axis)	-0.33	1.58	- 4.06 – 2.89	- 0.18	1.30	- 3.97 – 2.44	- 0.16	- 0.72	0.41	0.579

MP – mirror position, SBP – self – balanced position, positive values mean that the head is in flexion, rotated to the left and tilted to the right in the SBP compared to the MP.

Table 4. The differences (degrees) in the consistency of the mirror positions and self - balanced positions for the rotations around x, y, and z-axis

Rotations	MP T1T2			SBP T1T2			Comparison MP vs SBP			
	Mean	SD	Range	Mean	SD	Range	Diff.	95 %CI		P value
								lower	upper	
Pitch (X – axis)	0.88	4.05	- 6.67 – 14.47	1.73	3.69	- 5.75 – 9.95	- 0.85	- 2.29	0.58	0.237
Yaw (Y– axis)	-0.10	2.66	- 8.34 – 7.02	- 0.24	3.18	- 8.55 – 8.44	0.14	- 0.57	0.85	0.693
Roll (Z-axis)	0.25	1.77	- 2.88 – 3.76	0.41	1.88	- 3.99 – 5.16	0.21	- 0.35	0.77	0.456

MP – mirror position, SBP – self – balanced position, positive values mean that the head was more flexed, rotated to the left and tilted to the left during the first capturing.



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