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Title: Digital Live-tracking 3-D Mini-sensors for Recording Head Orientation During Image Acquisition

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Digital Live-tracking 3-D Mini-sensors for Recording Head Orientation During Image Acquisition

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Abstract

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Introduction

The relatively recent transition in orthodontics from 2-D to 3-D imaging and from analog to digital technology has created renewed impetus for finding a versatile method for establishing accurate and reliable head positioning during the acquisition of serial records. During the analog era orthodontists utilized cephalostats to orient radiographic films for diagnosis and for tracking longitudinal changes resulting from either growth or treatment. In the digital era, head orientation for the virtual patient presents a new challenge. When viewing a digital image on a computer screen there is no external reference to establish the natural orientation of the head and teeth. Cone beam computerized tomography (CBCT) and 3-D photographic imaging offer new possibilities for more comprehensive diagnosis and treatment planning in clinical orthodontics in that they offer far more information than the previous bi-dimensional records. However, additional tools are required to achieve accuracy and reliability in the capture of these images, and proper orientation is important for future superimposition of the images to assess change. Matching records taken at two different times requires a more complex computer registration than was heretofore necessary. This research project addressed the issue of recording head position when it is unrestrained as it is during image capture for 3-D photography or CBCT.

Head orientation has been a subject of great interest for clinical and research orthodontists for more than a century. In 1882, the General Congress of the German Anthropology Society agreed on a standard skull orientation proposed by Von Ihering.[1, 2] His suggestion, was that a line, named Frankfort Horizontal, extending from the upper ridge of the external auditory meatus to the most inferior portion of the orbit should be parallel to the floor. This strictly anatomic method of skull orientation could only be used for dry skulls, plaster facial moulages and dental casts.[3] When Broadbent[4] and Hofrath[5] proposed radiographic cephalometry in 1931, for the first time it was possible to study living human heads and because of their proposed stereotactic head holding device, the cephalometer, it was possible to study human facial growth longitudinally. The positioning of the head in the cephalostat initially chosen for this purpose was the orientation proposed by Von Ilhering, i.e., the Frankfort Horizontal. However, in 1956, Downs, utilizing photographs, demonstrated variation in the Frankfort Horizontal Plane when individuals were in natural head posture.[6] This prompted Moorrees and Kean, in 1958, to introduce in the orthodontic literature a physiologic position, Natural Head Position (NHP). NHP is determined largely by the visual axis and can be obtained by having the individual stand and look at the horizon. Alternatively, a mirror can be placed in front of the subject and the person asked to look at his or her own eyes in the mirror. NHP was originally proposed by Broca[7]to replace the anatomic method utilizing the Frankfort Horizontal plane.[8] Vig et. al. observed changes in NHP as a result of respiratory obstruction and discussed that posture and respiration had implications in the control of growth and the establishment of dentofacial morphology.[9]

Several authors tested the reliability of NHP in two dimensions using lateral cephalometric radiographs.[8, 10-15] Others used photographs in addition to cephalograms to help in testing the reproducibility of NHP [16, 17]. In all these studies, the evaluation and comparison of NHP utilized 2-D images. Reproducibility of natural head position has been evaluated for the capture of 3-D images by Xia and Gateno[16], who achieved NHP for stereolithographic skull models of patients with dentofacial deformities with two different methods. The first consisted of a laser scan capturing the facial soft tissues surface and matching it with a rendered composite skull model. The second technique, used a gyroscope attached to a face bow that provided the pitch, yaw and roll angulations of the patient`s head, which was used to reorient the skull on the computer. The reproducibility of head position in 3-D was also studied by Soncul and Bamber. Using a facial laser scan, a headrest and a spirit level, they showed high accuracy in reproducing head orientation; however, the Frankfurt plane was utilized rather than NHP.[17]

The objective of this study was to test the effectiveness of the mini-sensors in achieving repeatable head positioning. Because currently available imaging equipment is not designed for a standing patient, it was necessary in this study to have our test subjects sit, rather than stand, although a mirror was used in front of the subject to simulate NHP. The ultimate goal of this project will be to redesign the imaging equipment, if necessary, and utilize the 3-D sensors to record NHP.

Materials and Methods

Twenty volunteers (13 males and 7 females; mean age 32.80±8.7 years; range 20.3-55.6 years) were selected for this study. The sample included adult subjects of both genders. The exclusion criteria were 1) presence of dentofacial deformities, 2) facial hair, 3) orthodontic appliances, 4) clinical diagnosis of asymmetry, 5) pace-maker and 6) lip incompetence. The protocol was approved by the Biomedical Institutional Review Board and informed consent was obtained from all subjects.

3-D surface images of each patient were acquired using a 3dMDface System (3dMD, Atlanta, GA, U.S.A) on the same day (Figure 1), in 4 different situations: (1) patient in unrestrained head position; (2) repeated picture with patient in unrestrained head position; (3) patient in unrestrained head position wearing a headset with tracking sensors and (4) repeated picture of patient in unrestrained head position wearing a headset with tracking sensors (Figure 2).

The seating for 3-D photograph acquisition utilized an adjustable chair that allowed: (1) the ability to adjust the seat's vertical height to accommodate subjects of varying heights and (2) a back support to help the subjects simulate their standing posture. Because the subnasal and submental regions are prone to data loss and artifact, proper head posture ensured that these regions were visible to the imaging sensors of the camera. If the subject's head tilted forward even a few degrees these facial regions were often obliterated and it was necessary to remind the subject to "sit up straight". In addition to obvious signs of facial tension (e.g., furrowed brows) or emotional expressions, operators paid attention to the subject's mouth and eyes. The subject's eyes were open and the mouth closed during capture, with the lips gently pressed together to avoid variations in lip posture.

For all situations, patients were asked to sit in front of a mirror,[18] look forward, and try to position their facial midline with a "true vertical" tape (positioned at the center of the mirror). An assistant helped position each subject by moving the chair into the camera viewing area (Figure 3). The assistant did not ask the subject to move the head/neck at any time during initial pictures with or without sensors. Between each acquisition, the volunteer was asked to stand, walk around and move their chair, in an attempt to minimize bias in the reproducibility of repeated pictures. For the without sensor initial (photograph 1) and without sensor repeated photograph (photograph 2), the patient was simply asked to find their perceived most comfortable position.

For the third and fourth acquisitions, 3-D Guidance trackSTAR, a 3-D real time tracking system consisting of miniaturized 6 degrees of freedom sensors (Ascension Technology Corporation, Burlington, VT, U.S.A), was used. The 3-D Guidance trackSTAR is an electromagnetic tracking system where a mid-range transmitter generates pulsed DC magnetic fields for high accuracy tracking of the position of attached mini-sensors. This system is designed to also be used in surgical navigation systems that follow anatomic bodies, instruments, or devices in the operative scenario. The system provides tracking of actual object positions in relation to the skull base and assistance for manipulating the object into the desired configuration. In this study, three individual mini-sensors of the 3-D guidance track-star system were attached to a commercially available band type hearing protector, ordinarily used for reducing the effects of shop or industrial noise. A hole was made in each auricular part of the protector to fit two sensors (each 1 mm outer diameter X 10 mm in length). The third sensor was attached to the middle of the band (Figure 4). All three sensors were plugged into a main unit, which communicates to the computer via a universal serial bus port (USB). Software (Cubes©) tracks the real time coordinates of the 3 attached sensors. The sensors were fitted in the patient ears and the band was pushed to the neck. Removal of sweatshirts with hoods, and tucking in collars and other clothing articles around the neckline facilitates adequate capture of the neck, mandible, and ear. Each of the three sensors recorded 6 degrees of freedom in head position: the X, Y, Z, (inferior-superior, postero-anterior and latero-lateral) distances from the center of the transmitter, and the X, Y and Z rotational coordinates (roll, pitch and yaw data) for each patient at the moment of acquisition of the third and fourth pictures. For the photographs captured with sensors, an assistant helped with chair movement and head tilt to reach the same X, Y and Z position (in mm) and the same pitch, yaw and roll angulation (in degrees) from initial (photograph 3) to repeated (photograph 4). It was theorized that the closer the values are for X, Y and Z between the photograph 3 and 4, the better the reproducibility should be.

After acquisition, each image was loaded into the software 3dMD Patient (3dMD, Atlanta, GA, U.S.A) and exported as a .STL binary file. All the .STL files were converted to .IV extension using the STL to SGI Inventor 2.0 (IV) Utility Beta (developed by Reuben Reyes, hitechmex@austin.rr.com). The software CMF application (developed at the M.E. Müller Institute for Surgical Technology and Biomechanics, University of Bern, Switzerland, under the funding of the Co-Me network, http://co-me.ch)[19] was used to locate anatomic landmarks in the 3-D photos and to measure landmark distances between acquisitions. Landmarks were placed in eight different sites for each picture by the same operator as follows: (1) nasion, (2) tip of nose, (3) subnasale, (4) right lip commissure, (5) left lip commissure, (6) midpoint of upper lip vermilion, (7) midpoint of lower lip vermilion, (8) soft tissue B-point (Figure 5). For 10 subjects the landmark identification was repeated 3 times to assess intra-observer reliability. Distances between the same landmarks were measured between images 1 and 2 and between images 3 and 4.

Statistical Analysis

To assess the reliability of landmark identification in 3-D photographs, intra-class correlation coefficients (ICC) were calculated for each landmark at each coordinate. A mixed effect analysis of variance model was used in SAS systems 9.2 to test absolute agreement and consistency.

Descriptive statistics were used to show the mean values and standard deviation of inter-landmark distances on repeated acquisitions of head position without and with the use of 3-D live tracking sensors. Box plots were used to graphically display the variability of inter-landmark distances data. Student’s t-test was conducted to compare replicability of head position with and without sensors. The probability of greater than 2mm difference between the two methods was calculated.

Results

To assess the reliability of identification of landmarks in 3-D photographs, intra-class correlation coefficient (ICC) revealed good to excellent reliability.

The average distances between landmarks in acquisitions 1 and 2 (unrestrained head posture without sensors) were 17.43mm ± 0.32 SD with consistent findings for all landmarks studied. The average distances between landmarks in acquisitions 3 and 4 were 6.17mm ± 0.15 SD; these findings were also consistent with all landmarks measured (Table 2 and Figure 6).

All inter-landmark distances were highly significantly different between the two methods, with all p-values being smaller than 0.01 (Table 3). The probabilities that the differences between the two methods (without and with sensors) are greater than 2mm for each landmark are given in the last column of Table 3.

Discussion

The present study evaluated the improvement in reproducibility of unrestrained head positioning with the aid of 3-D live tracking sensors. With the advent of technologies for 3-D imaging in the health sciences, it is important to establish accurate and reliable methods for standardizing the acquisition and measurement of the images. Three dimensional imaging software programs now contain tools for rotation and translation of 3-D renderings, volumes, or surfaces, as well as registration of different acquisitions with landmark, volume, or surface based methods, but there is no available external reference for head positioning. In particular, no stable reference structure exists in 3-D facial photographs for soft tissue assessments in longitudinal studies. This work tested the use of 3-D mini-sensors to approximate the same head positioning between image acquisitions. The intention was to minimize any error that differences in head position would add to the data; however, at different time points, changes in anatomic structures and landmarks can occur and conventional registration of the images is still required for longitudinal superimpositions.

In our study we attempted to reproduce unrestrained head position 3-dimensionally utilizing 6 degrees of freedom. When comparing the repeated acquisitions of head position with and without the tracking system in this study, a statistically significant difference was found between the inter-landmark distances with the 2 methods. There was also a high probability of the difference between the two methods being greater than 2mm. The inter-landmark distance between repeated acquisitions of head position with the sensors was on average approximately 6mm compared to the approximately 17mm observed without the use of the sensors. These findings show that use of sensors aided reproducibility of unrestrained head position.

In the present investigation the interval between photographs was only ten minutes, and future longitudinal studies could pose greater challenges to the reproducibility of the 3-D head position. For this study and for longitudinal assessments, the cameras were and would need to be kept in a separate room with the fixed stands taped to the floor. In longitudinal studies of 2-D images acquired at 2 month intervals, Solow and Tallgren[10] used the subject's "orthoposition", which was obtained in standing subjects, with a head holder and images taken at 2 month intervals. They relied on the subject's "self balance" i.e., the patient's own feeling of natural head position after extending and flexing their head with decreasing amplitude until a feeling of "natural balance" was achieved. Other longitudinal studies have evaluated reproducibility in head positioning at longer time intervals. Cooke and Wei[12] compared different head positioning techniques (with and without ear rods and/or mirror) at 3 different time intervals. At short intervals between acquisitions (4-10 minutes), the best results were in the group without ear rods using a mirror as reference, while after 3 to 6 months, they found that head position was more reproducible using ear rods. In a later study, Cooke[20] also found that the reproducibility of NHP decreases with longer intervals between acquisitions, but the variation on NHP to true vertical was still less remarkable than the variation to true vertical using intracranial references.

In a previous study attempting to reproduce head orientation in NHP, Usumez and Orhan[13], introduced a device with two inclinometers attached to a pair of eyeglasses: one recorded the pitch and the other recorded the roll angulations. The drawback of this type of set-up is that if it was to be employed for clinical situations, the eyeglasses would interfere with the ability to evaluate the subject without the distraction. In the present study, each one of the three sensors recorded 6 degrees of freedom simultaneously: pitch, roll and yaw inclinations and distances of the head position to the transmitter. In addition, the headset was worn behind the head and thereby did not distort the subject's facial image.

This study's findings suggest that a digital 3-D tracking system is a promising tool for head position reproducibility,but the study also highlighted limitations in current 3-D assessment of treatment outcomes. First, stereophotogrammetry systems and other 3-D imaging systems such as CBCT scanners do not allow images to be acquired in natural head position. Superimposition of images acquired at different time points relies on the ability to reproduce head position, and if traditional means of reproducing head position (such as capturing a person in NHP) are not achievable, then determining a new method of acquiring images with a reproducible head position is important. Second, if both 3-D photographs and CBCT images are necessary, it would be ideal for both 3-D images to be taken simultaneously as it has been done in two dimensional studies using cephalograms and 2-D photographs such as that of Solow and Tallgren[10]. Given the current configuration of the 3-D stereophotogrammetry imaging equipment, it is not clear how this could be accomplished.

If the use of sensors to achieve the goal of reproducible head position is the future, then the construction of a more robust headset to hold the sensors is needed. An adjustable and measureable inter-ear distance and a posterior screw that creates a tripod effect with the ear-buds would be an improvement to the current study head-set design. Additionally, the imaging software should be able to acquire the photograph, CBCT, and sensor coordinates simultaneously. In this study, two different software programs were used to measure the coordinates and to capture the image. The operator needed to click one button for image acquisition and another one for coordinate recording, which creates a very brief time lag between the two clicks. The use of an automated chair that is movable in the anterior-posterior and superior-inferior axes would aid patient positioning.

The ultimate goal would be to have a system which eliminates, or at least significantly decreases, the need for operator guided patient positioning. Future investigations are needed to improve the use of tracking sensors for standardization of head orientation to allow their use in daily clinical practice. A possible approach to facilitate the use of 3-D sensors includes the development of software to capture the patient´s head coordinates at the time of initial acquisition and use this information to relocate the generated surface models of later acquisitions to match the first. Another approach that can already be applied to longitudinal studies is to use the patient´s initial head coordinates to assist in reorienting the patient's head to the same position as the initial acquisition, automatically acquiring the picture when this position is achieved. The proposed standardization and recording of head positioning in this study differs from procedures currently allowed by commercial software such as Geomagic, 3dMDVultus, and InVivo that use best-fit 3-D software to correct some of the above problems, as those software tools do not take head positioning into account.

Additional future development might include having a sound signal to alert the patient when he or she approaches the head orientation of an earlier image which is trying to be matched. Another possibility could be the use of a computer display of the patient's current head position over a semi-transparent previous image to help the patient and/or operator visualize changes needed to achieve the desired head position. Although it is unrealistic to believe that mini-sensors can ever achieve perfect reproducibility of head position, there is little doubt that this methodology will have to be perfected before it is suitable for important research or clinical use.

Conclusions

Reliable head orientation during image capture with 3-D photography or CBCT continues to be an important aspect of orthodontic diagnosis, treatment, and subsequent assessment of treatment results. The goal of any system designed to improve an orthodontist's ability to properly orient 3-D virtual images is to be able to ascertain and record a repeatable head position. This physiologic goal will greatly improve the value of the three-dimensional digital images which have so dazzled the orthodontic specialty over the last decade. As technology progresses and 3-D imaging supersedes 2-D imaging, and the traditional means of standardizing head position are no longer as easily employable, mini-sensors have the potential to become an important aspect of capturing the same head position at different time points. Based on the findings of the current study, the following conclusions can be made:

1. The use of mini-sensors improves the repeatability of stereophotogrammetric photographs taken by the 3dMD camera system.
2. Currently, the use of mini-sensors does not eliminate the need for registration procedures performed by imaging software for evaluation of like images taken at different time points.

Although the use of mini-sensors is a promising tool for the future, several improvements are required before they can be incorporated practically for research or clinical use.

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Figure 1: Computer (A) connected to a multi-lens camera (B) used to capture the 3-D surface image of a patient who was asked to look at the mirror (C) and center his face to the vertical line. The 3-D real time tracking system developed by Ascension Technology Corporation used in this study was composed by a main unit (D) that communicates to the computer providing the coordinates of the sensors (E) which are captured related to a mid-range transmitter (F).

Figure 2: 3-D surface images overlaid as follows: A - Patients in unrestrained head position and the repeated picture (green image); B - patient in unrestrained head position wearing a headset with tracking sensors and the repeated picture of patient in NHP wearing a headset with tracking sensors.

Figure 3: Computer screen showing a patient with his face well-framed in the capture area for the camera acquisitions from left and right angles.

Figure 4: Sensors were attached to a commercially available band type hearing protector. A hole was made in each auricular part to fit two sensors and the third was attached to the middle of the band

Figure 5: Landmarks used for evaluation of distances between acquisitions. (1) nasion, (2) tip of nose, (3) subnasale, (4) right lip commissure, (5) left lip commissure, (6) midpoint of upper lip vermilion, (7) midpoint of lower lip vermilion, (8) soft tissue B-point.

Figure 6: Box plots showing variability of inter-landmark distances data, where in Li, i=landmark number. L1 - Left Lip Commissure, L2 - Right Lip Commissure, L3 – Midpoint of the Lower Lip Vermilion, L4 - Soft Tissue B-Point, L5 - Nasion, L6 - Subnasale, L7 - Tip of Nose, L8 – Midpoint of the Upper Lip Vermilion.

Table 1 – Reliability estimated by intra-class correlations for each of the landmarks and for each X, Y, and Z coordinate.

Landmark	Intraobserver Reliability		
	X	Y	Z
Left Lip Commissure	0.97	0.99	0.99
Right Lip Commissure	0.99	0.99	0.99
Lower Lip	0.60	0.54	0.99
Nasion	0.99	0.99	0.99
Subnasale	0.85	0.99	0.99
Soft Tissue B-Point	0.98	0.99	0.99
Tip Nose	0.99	0.74	0.99
Upper Lip	0.99	0.99	0.99

Table 2 – Descriptive statistics of inter-landmark distances on repeated acquisitions of head position without the use of 3-D live tracking sensors and with its use.

	Left Lip Commissure	Right Lip Commissure	Midpoint of the Lower Lip Vermilion	Soft Tissue B-Point	Nasion	Subnasale	Tip of Nose	Midpoint of the Upper Lip Vermilion
Without Sensors	16.85 ± 9.59	17.64 ± 9.85	17.61 ± 9.89	17.66 ± 9.71	16.97 ± 10.3	17.5 ± 9.92	7.57 ± 10.26	17.63 ± 10.03
With Sensors	6.34 ± 2.38	6.43 ± 2.84	6.16 ± 2.70	6 ± 2.62	6.18 ± 2.72	5.99 ± 2.78	6.21 ± 2.72	6.06 ± 2.77

Table 3 – Difference between the two methods to reproduce head position (without and with sensors). T-statistics, corresponding two-sided p-values, and the probability that the difference between the two methods is greater than 2mm, under the assumption that the true mean difference is 0: P(đ>2mm)

Inter-landmark difference **(Without Sensors-With Sensors)**	**t-Statistic**	**p-Value**	**P(đ >2mm)**
Left Lip Commissure	4.34	**0.0004**	0.21
Right Lip Commissure	4.41	**0.0003**	0.22
Lower Lip	4.45	**0.0003**	0.22
Soft Tissue B-Point	4.62	**0.0002**	0.22
Nasion	4.27	**0.0004**	0.22
Subnasale	4.49	**0.0002**	0.22
Tip of Nose	4.35	**0.0003**	0.23
Upper Lip	4.51	**0.0002**	0.22

Figure1
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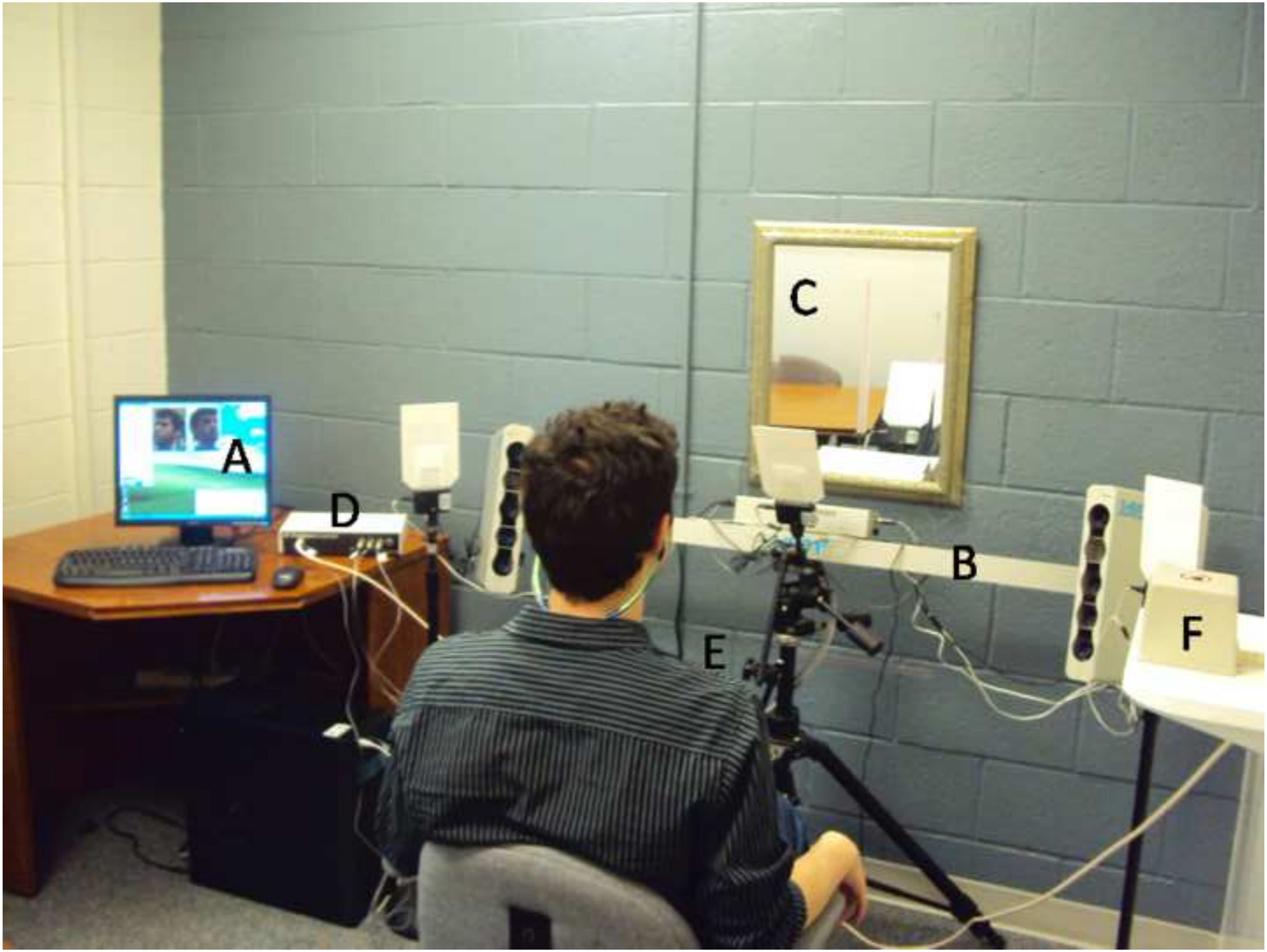

Figure2

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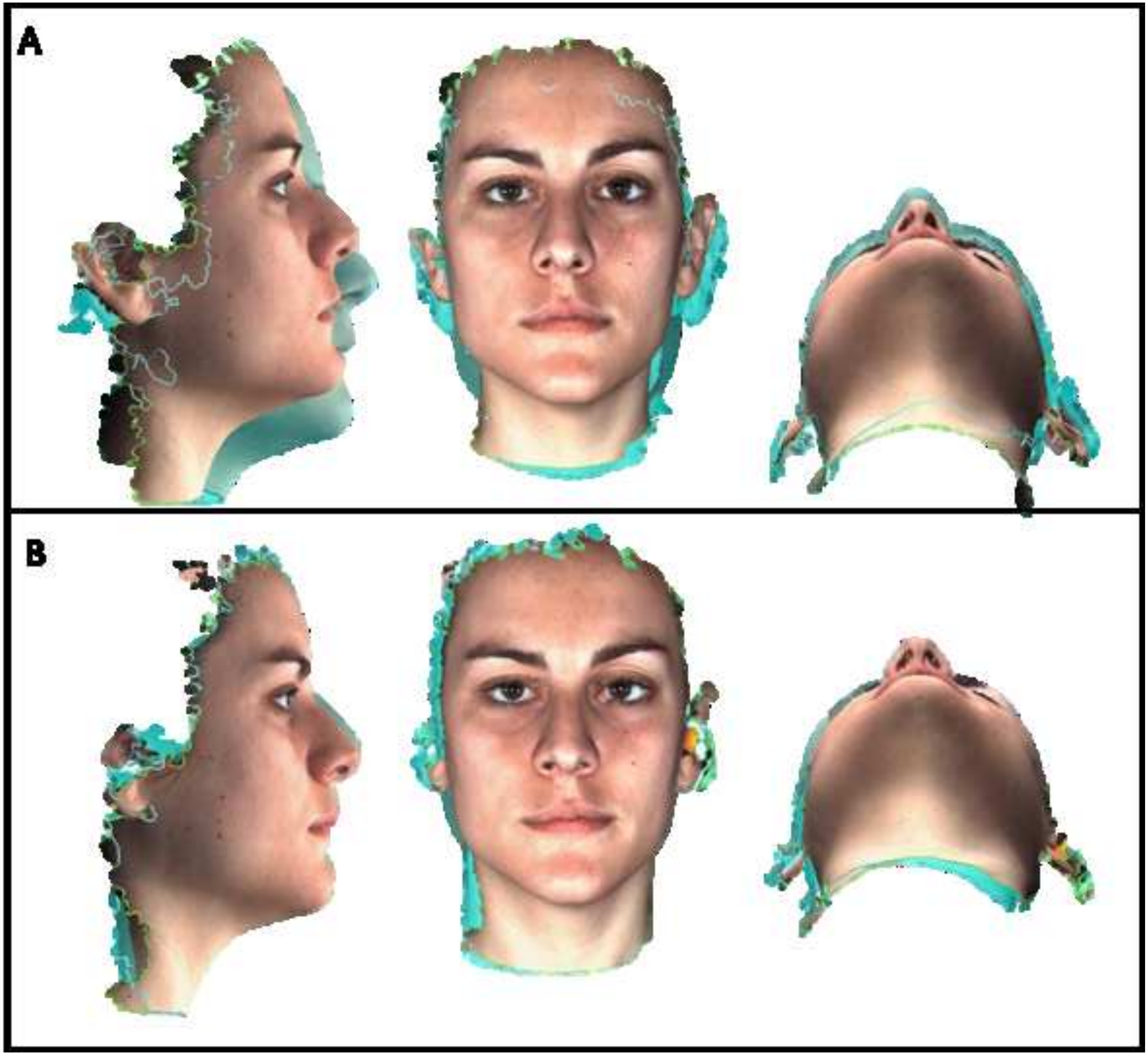

Figure3
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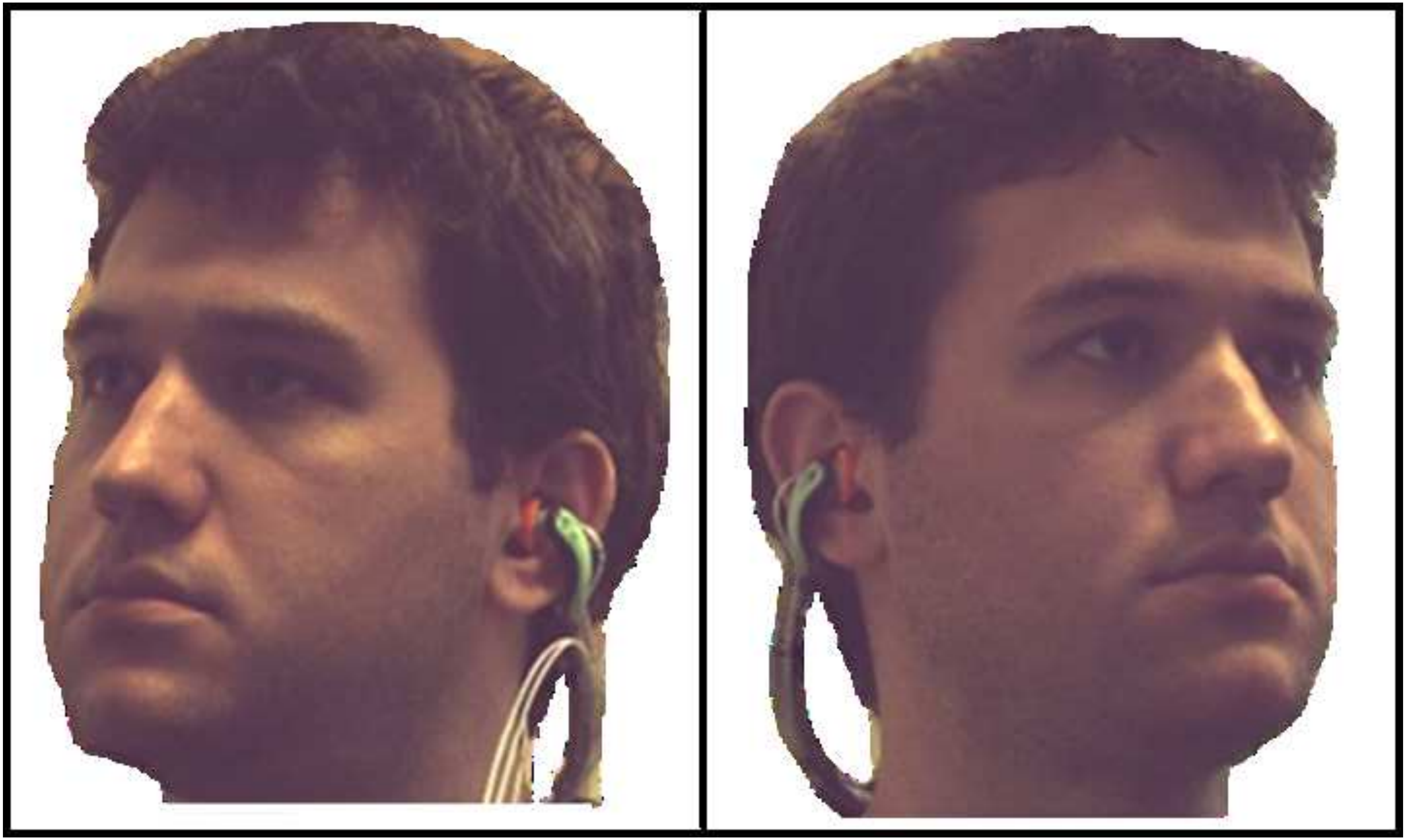

Figure4

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Figure5

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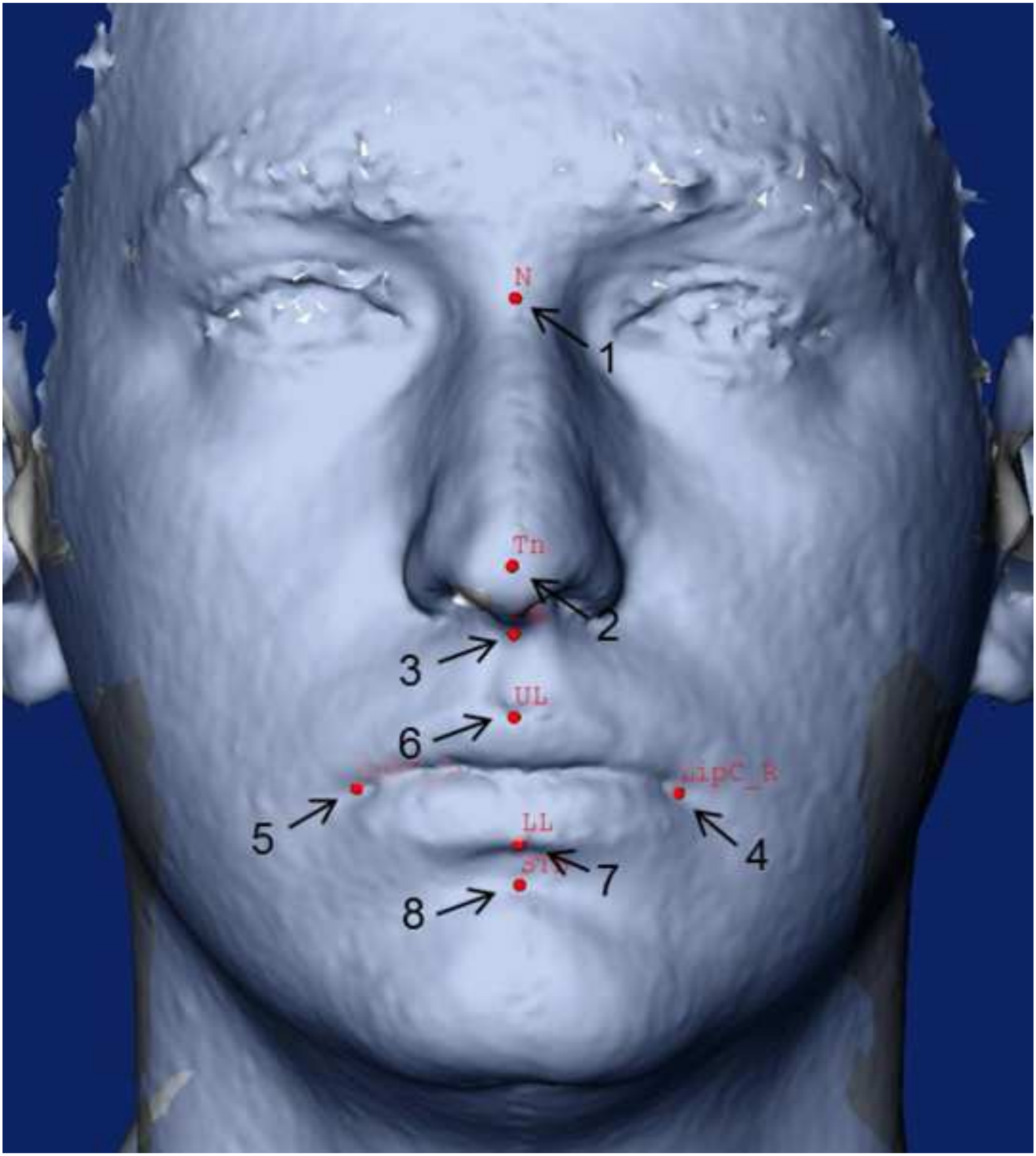

Figure6

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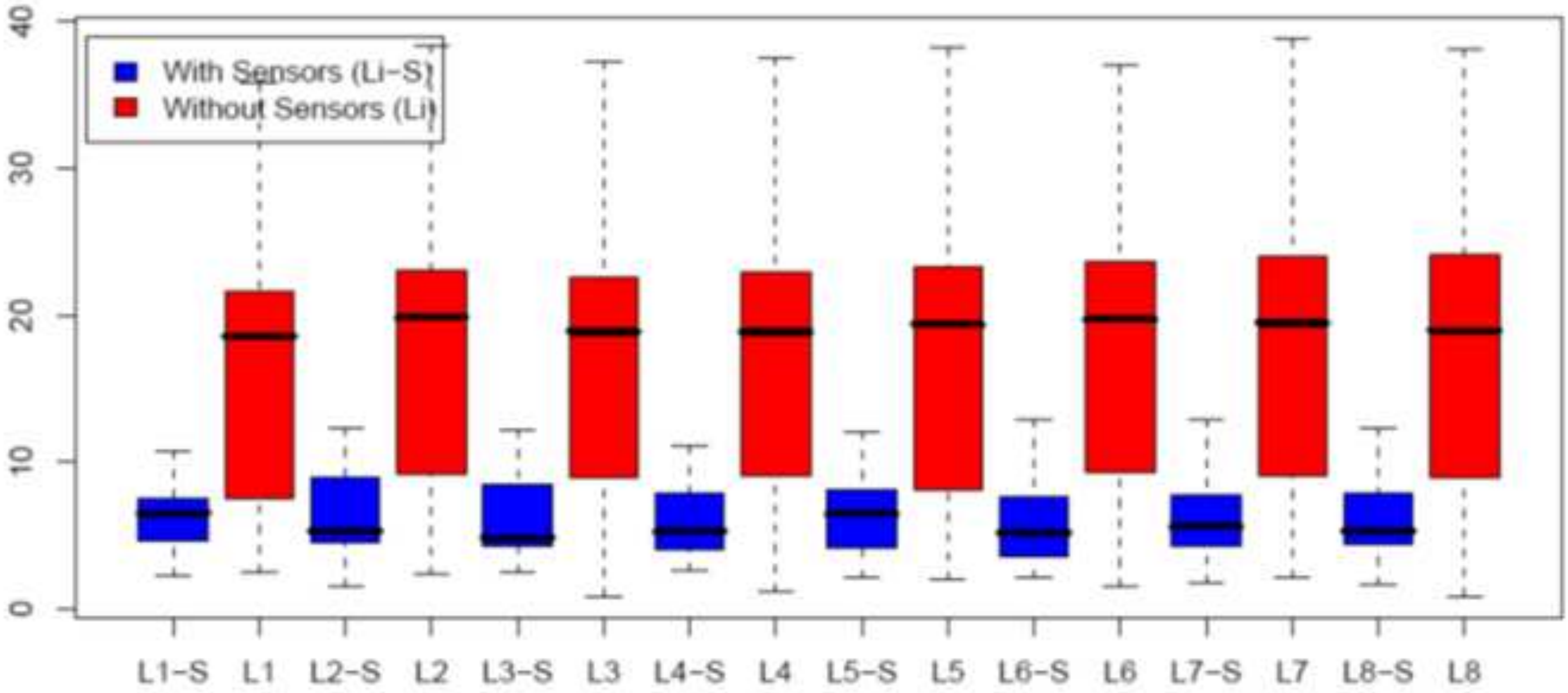

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***Revision Notes (no author identifiers please)**

Dr. Vincent G. Kokich
Editor-in-Chief
American Journal of Orthodontics and Dentofacial Orthopedics

RE: Item by item response to reviewer comments on paper no: AJODO-D-11-00014

Dear Dr. Kokich:

We have carefully revised the manuscript to address all the reviewers' comments.

Reviewer #1

In the "original submission" where and how the collected 3D sensor data was used was missing and the study made no sense as such.

In the "revision" the author/s clarified this adding the phrase "For the reproducibility pictures with sensors, an assistant helped with the chair movement to reach the same X, Y and Z (in mm) and the head tilt trying to reach the same pitch, yaw and roll (in degrees)." in the Mat&Met section.
Now everything is clear.

Congratulations.

Only in the discussion section latter paragraphs seem to be numbered and this should be corrected.

Thank you for the review, we have corrected the discussion section and because of that, we changed the conclusions as well.

Reviewer #2:

This manuscript remains well written. The authors have addressed the most comments in our previous reviews. However, a key issue still remains unsolved: whether 3dMD is capable of capturing NHP? I personally have a 3dMD camera, and a lot of time and experience on using this camera. Unlike Cyberware laser scanner, 3dMD camera is not calibrated to true horizontal or true vertical, thus the head orientation captured by the camera is not the actual head orientation in live. This was confirmed by 3dMD company. Just do a simple test, turn your face 45 degree and to see if 3dMD can capture this orientation. Unless the authors have the newest special beta version of 3dMD that was just incorporated the function of capturing NHP, I believe this study design flaw still remains. Bottom line: many published articles indicated the variability of self-balanced NHP is around 2 degrees. If the authors have the newest beta version of 3dMD, why they need to use those sensors in addition to 3dMD? We use the technology is that because we need the technology to solve problem. We should not abuse technology just because we have a technology in hand. Until these basic questions are answered, I do not think it should be accepted for publication.

This reviewer misinterprets the goals of the study for two reasons. First, the purpose of the study was not to capture natural head position, but to reliably record unrestrained head position. Second, the fact that 3dMD camera does not have a true vertical or horizontal line according to the reviewer does not affect the reproducibility of head position in different pictures by the camera's software.

The simple test proposed by the reviewer is shown in Figure 2, with the exception that the head orientation wasn't changed by 45 degrees. Note that for both 2A and 2B, two pictures were taken and opened at the same time by the software. In Figure 2A, you can appreciate that, in the transparent image, the patient's face is forward, lower and more to the left (check left ear position in the frontal picture) than the solid image. That explains how the 3dMD camera imports different real head positions to the computer.

The differences in these positions are due to the fact that the software captures the patient's head orientation according to: 1) 3dMD camera position and 2) patient position. Since the camera wasn't moved during the entire study, the only variable left is the second: the patient position.

The techniques used to achieve NHP in several previous studies use profile pictures or lateral cephalometric radiographs for evaluation. Both are 2-dimensional images and some of the variables that we evaluated in this study cannot be analyzed with only 2-dimensional imaging. Inclination of the x axis (pitch) is measurable with profile exams; however, inclinations of the y (yaw) and z axis (roll) cannot be evaluated with only the profile view. In addition to the inclinations, the sensors can provide the same position in space, without the need of another apparatus, such as the cephalostat.