Development and Validation of a Digital Head Posture Measuring System

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• PURPOSE: To report the accuracy and repeatability of a new digital head posture measuring system.
• DESIGN: Prospective study, clinical laboratory investigation.
• METHODS: The digital head posture measuring system consists of a head-mounted motion tracker, a standard personal computer, and customized software to sample and display 3-dimensional (3D) head posture in real-time. Using a mechanical head posture measuring device as a reference, 3D head positions of an artificial head and 12 human subjects were recorded with the digital head posture device. Accuracy of the digital device outputs, relationship between digital outputs and actual head rotations, and repeatability of the tests were analyzed.
• RESULTS: The digital head posture device showed consistent outcomes when compared to the mechanical one. The digital outputs of 3D rotations are very close to actual artificial head and human head rotations. The correlation coefficients of the linear relationship between the digital outputs and actual head movements were greater than 0.99. Repeatability tests for the artificial head and human subjects for all 3D rotations had 95% limits of agreement angles less than ±6 degrees and ±8 degrees, respectively.
• CONCLUSIONS: The digital head posture device is an acceptable device with high accuracy, repeatability, and validity in measuring head posture in 3 dimensions. (Am J Ophthalmol 2009;147:1092–1100. © 2009 by Elsevier Inc. All rights reserved.)

ANOMALOUS HEAD POSTURE IS A COMMON CLINICAL symptom caused by ocular, orthopedic, and neurologic disorders.1-3 While a variety of conditions may be responsible, anomalous head posture attributable to visual system abnormalities, or ocular torticollis, is quite common in children. For example, it has been found that about 62% of child patients with nystagmus have anomalous head posture.4 There is evidence that early corrective surgery for children with ocular torticollis improves visual function5 and may prevent musculoskeletal problems resulting from uncorrected ocular torticollis.2,3 Thus, an effective technique for accurate measurement of ocular torticollis in children is needed to assist with surgical planning. However, current techniques for measuring anomalous head posture, including a mechanical head posture device6 or a cervical range of motion device7 requires extensive patient cooperation not always available with children. This makes accurately measuring a young child's torticollis virtually impossible using such devices. The ideal device for measuring head posture requires little patient cooperation and provides instantaneous reliable measurements. When such a device is proven useful for children, it will be easily applicable for adult patients as well.

Head rotation about 3 axes is usually measured in degrees. We will use head-turn for rotation around the longitudinal axis (y-axis), chin-up/down for rotation around the interaural axis (x-axis), and head tilt for rotation around the naso-occipital axis (z-axis) of the head throughout the study.

In the present study, we have developed a digital head posture measuring system and tested it with an artificial head and normal human subjects. We will report the accuracy and repeatability of measurements.

METHODS

• DEVICES: Mechanical Head Posture Measuring Device. A mechanical head posture measuring device was used as the reference to validate our digital head posture device. It was mounted on the same helmet with the digital head posture device. The mechanical head posture measuring device consists of 2 intersecting plastic protractors, a grid pattern, and a laser. The grid pattern with marked angles was projected on to a screen and used in combination with the laser to measure head-turn and chin-up/down. The protractors were used to measure head tilt. A complete setting of the mechanical head posture device is shown in Figure 1.

The Digital Head Posture Measuring System. The digital head posture measuring system consists of a motion tracker mounted on an adjustable headset, a controller personal computer, and custom software for data recording and
visualization. A photo including mechanical head posture device and digital head posture measuring system is shown in Figure 2. The figure has 3 main parts: 1) a computer monitor showing numerical outputs and a simulated head; 2) a helmet with laser pointer and protractors; and 3) a pair of spectacle frames with the mounted motion tracker. The motion tracker can be mounted on either helmet or the frame. The motion tracker is commercially available and uses hybrid techniques including magnetometer, accelerometer, and gyroscope made by InterSense (Bedford, Massachusetts, USA). It uses a local-level geographic frame with its x-axis pointing north, y-axis east and z-axis down. The reported rotation angles can be described as a sequence of rotation applied to the device starting with its body axis initially aligned with its axis of the reference frame in space and resulting in the current orientation. For example, the sequence starts with a rotation of right head-turn about the z-axis, followed by a rotation of chin-up about the new y-axis (the axis of the device body), and followed by a rotation of head-tilt about the new x-axis (the axis of the device body). The software was written in C++ by one of our collaborators. Using the same coordinate frame as the tracker, the digital head posture measuring system continuously measures a patient’s head posture at a rate of 20 Hz and presents a real-time animation of a head movement on a liquid crystal display along with numerical readings. It records and saves the data into a computer file for offline analysis. The saved data include the initial head position, ending head position, and the difference between the 2 positions (head posture in degrees). It is claimed by the manufacturer that the tracker works with full 360 degrees range with angular accuracies of 0.25 degrees for chin-up/down and head tilt measurements and 0.50 degrees for head-turn measurements.

Artificial Head. To produce accurate head rotation, we developed an artificial head. The artificial head was built with a multi-directional rotation joint (Manfrotto, Bassano Del Grappa, Italy) that allows 3-dimensional (3D) movement and a foam head similar to the human head in size. A regular laser pointer was mounted on the artificial head close to the joint. When the laser was aligned with the center of the display grid pattern, horizontal and vertical rotations were projected on the display grid pattern. The intersecting protractors were set on top of the artificial head to measure head tilt.

- **PROCEDURES:** The mechanical head posture measuring device including protractors/laser pointer was used for both the measurement of artificial head and human subjects.

Measuring Rotations of the Artificial Head. The artificial head was placed 1.1 meters from the display grid pattern. Special care was taken to mount the laser close to pivot point of the head (at nose level) and level it with the
center of the display pattern. The laser and display pattern were used to measure head-turn and chin-up/down. The size of the display pattern covers 80H × 80W degrees.

One-dimension Rotations of the Artificial Head. The artificial head was rotated in horizontal, vertical, or torsional dimensions in 10-degree increments up to 40 degrees. Six tests for each head position were performed.

Three-dimension Rotations of the Artificial Head. To incorporate all abnormal head positions that can possibly occur in clinical patients, the artificial head was rotated in combination of horizontal, vertical, and torsional dimensions in 10-degree increments up to 30 degrees in each quadrant. The artificial head was directly rotated from an initial zero position to a final 3D position of head-turn + chin-up/down + head tilt. The difference between the initial position and the final position was recorded. No specific order of rotations was used. Each head position was tested 3 times for a total of 72 head positions in 4 quadrants.

Measuring Rotations of Human Subject’s Head. Twelve normal adult subjects (20 to 48 years old, 4 females and 8 males) with normal head posture and normal vision participated in the investigation. All head positions tested were 3D positions. Only adult subjects were selected to participate in the tests because the tests require subjects to be cooperative.

The distance from the screen to the center of subjects’ head was 1.1 meters. Subjects were seated and held their head at a primary position (0 degrees in all 3 dimensions) at the beginning of each trial. An adjustable head rest was placed against their backs to restrain their body’s translational movements. After the subject’s primary head position was set, the laser pointed to the center of the display pattern, and the protractor pointed to a zero position. The digital head posture measuring system was then zeroed by pressing the space bar on the computer. A location in the grid was given to the subjects; subjects turned their head to point a dot at the location with the laser, such as a 10-degree 3D head position of left head-turn, chin-up, and left head tilt. Subjects turned their heads in increasing angles in 10-degree increments to 30 degrees, as indicated by the dots in Figure 1. Each subject participated in 3 sets of tests for all 3D head positions in 4 quadrants, resulting in a total of 72 head positions for each subject. The subjects did not have any feedback from the digital outputs.
DATA ANALYSIS: Head position data from the artificial head and from normal subjects were analyzed graphically and statistically. Correlation coefficients for each rotation were calculated over the range of angles measured. The repeatability of the artificial head data and normal subject data was determined using 95% limits of agreement (LoA) between 2 of the 3 tests using Equation 1.\(^8\)

\[
95\% \text{ LoA} = \text{Mean} \pm 1.96 \times \text{Standard Deviation of Differences} \quad [1]
\]

To determine repeatability, the difference between Test 1 and Test 2, Test 2 and Test 3, and Test 3 and Test 1 were calculated along with the mean of Test 1 and Test 2, Test 2 and Test 3, and Test 3 and Test 1. These values were then used in Equation 1 to assess repeatability.

RESULTS

RESULTS FROM THE ARTIFICIAL HEAD: One-dimension Rotations of the Artificial Head. Average outputs of digital head posture measuring system for horizontal head-turn of the artificial head are displayed in Figure 3. In Figure 3, Top left, the head-turn outputs from the digital head posture measuring system are almost identical to the actual horizontal rotation of the artificial head. The correlation coefficient between the horizontal outputs and horizontal rotations is 0.99. Figure 3, Top right and Bottom left shows that the chin-up/down and head tilt outputs varied within 1 degree as the artificial head moved to different horizontal positions. Average outputs of digital head posture measuring system for chin-up/down of the artificial head are also almost identical to the actual vertical rotation of the artificial head. The correlation coefficient between the vertical outputs and vertical rotations is 0.99. Similar to the horizontal rotation of the artificial head, the horizontal and torsional outputs varied within 1 degree as the artificial head moved to different horizontal positions. Average outputs of digital head posture measuring system for chin-up/down of the artificial head are also almost identical to the actual vertical rotation of the artificial head. The correlation coefficient between the vertical outputs and vertical rotations is 0.99. Similar to the horizontal rotation of the artificial head, the horizontal and torsional outputs varied within 1 degree as the artificial head moved to different horizontal positions.

FIGURE 4. Measured average outputs of the digital device for 3-dimensional (3D) rotations of the artificial head. (Top left) Outputs of head-turn vs horizontal rotations. Data for right head-turn are in the right side of the figure (quadrants I and IV); data for left head-turn are in the left side of the figure (quadrants II and III). (Top right) Outputs of chin-up/down vs vertical rotations. Data for chin-up rotations are in the upper part of the figure (quadrants I and II); data for chin-down rotations are in the upper part of the figure (quadrants III and IV); (Bottom left) Outputs of head tilt vs torsional rotations. All measured outputs of the digital device are close to the actual rotations. All correlation coefficients are greater than 0.99. I, II, III, and IV represent first to fourth quadrants.

\[\text{FIGURE 4. Measured average outputs of the digital device for 3-dimensional (3D) rotations of the artificial head. (Top left) Outputs of head-turn vs horizontal rotations. Data for right head-turn are in the right side of the figure (quadrants I and IV); data for left head-turn are in the left side of the figure (quadrants II and III). (Top right) Outputs of chin-up/down vs vertical rotations. Data for chin-up rotations are in the upper part of the figure (quadrants I and II); data for chin-down rotations are in the upper part of the figure (quadrants III and IV); (Bottom left) Outputs of head tilt vs torsional rotations. All measured outputs of the digital device are close to the actual rotations. All correlation coefficients are greater than 0.99. I, II, III, and IV represent first to fourth quadrants.}\]
horizontal and vertical outputs varied within 1 degree as the artificial head moved to different torsional positions (see the Table for details).

The results from pure horizontal or vertical or torsional rotations of the artificial head clearly demonstrated the 1-dimensional (1D) movements produced little to no cross-talk to other dimensions.

Three-dimension Rotations of the Artificial Head. For rotations of the artificial head in all 3 dimensions concurrently, outputs of digital head posture measuring system for each head position are plotted in 4 quadrants according to the direction of head rotation (Figure 4). Data for combined 3D rotations with right head-turn are in the right half panel (quadrants I and IV); combined 3D rotations with left head-turn are in the left half panel (quadrants II and III); chin-up is in the upper panel (quadrants I and II); and chin-down is in the bottom panel (quadrants III and IV). Data for right and left head tilt in combination with head-turn and chin-up/down are presented in each quadrant. Outputs of digital head posture for head-turn, chin-up/down, and head tilt are very close to their actual mechanical head posture angles (Figure 4). The correlation coefficients between the outputs of digital head posture measuring system and movements of the artificial head are higher than 0.99.

To determine the repeatability, 95% LoA were computed between the 3 tests of all head positions using Equation 1. Plots of difference vs mean for 10-degree increments for all 3D movements were created to show these limits of repeatability.

For head-turns, the range of maximum LoAs was found to be less than ±2 degrees for head-turns of 10 degrees; less than ±3 degrees for 20 degrees; and approximately ±6 degrees for 30 degrees (Figure 5, Top left and right and Bottom left). In Figure 5, the data for right head-turn in combination with right/left head tilt and chin-up/down (head rotations in quadrants II and III) are plotted on the right side of the figure; and the data for left head-turns in combination with right/left head tilts and chin-up/down (data from quadrants I and IV) are plotted on the left side of the figure. There are three sets of repeatability data from three tests: Test 1 vs Test 2, Test 2 vs Test 3 and Test 3 vs Test 1. These data were plotted with the same symbols because the testing conditions were identical. For chin-up/down, the range of maximum limits of repeatability was found to be ±2.0 degrees for an actual 10 degrees movement; approximately ±2.0 degrees for 20 degrees; and ±3.5 degrees for 30 degrees. For head tilt, the range of maximum limits of repeatability was found to be less than ±3.5 degrees for head tilt of 10 degrees, approximately ±5.5 degrees for 20 degrees, and less than ±6.5 degrees for 30 degrees.

RESULTS FROM NORMAL SUBJECTS: All 12 subjects successfully completed the 3 tests and average outputs for
FIGURE 6. Average outputs of the digital device for 3D rotations of human subjects. The conventions are identical to Figure 4. (Top left) Head-turn outputs vs horizontal rotations. (Top right) Chin-up/down outputs vs vertical rotations. (Bottom left) Head tilt vs torsional rotations. All correlation coefficients are greater than 0.99.

FIGURE 7. Bland-Altman plots demonstrating means and differences of measurements between Test 1, Test 2, and Test 3. The mean of the differences and the 95% CI of the differences are shown in Figure 7, Top left for 10 degrees, Top right for 20 degrees, and Bottom left for 30 degrees of horizontal rotations, respectively. The conventions are identical to Figure 5.
head-turn, chin-up/down, and head tilt were computed and displayed in Figures 6, Top left and right and Bottom left. In Figure 6, the head position data are plotted in 4 quadrants in accordance with the direction of head rotation, the same as in Figure 4. For head-turn (Figure 6, Top left), data for combined 3D rotations with right turn are displayed in the right side of the figure (quadrants I and IV), with left turn in the left side (quadrants II and III). When left turns were associated with left tilts and when right turns were associated with right tilts, outputs of head-turns were lower than the actual rotations. When right turns were combined with left tilts and left turns were combined with right tilts, average outputs of the digital head posture measuring system were nearly identical to rotations of the mechanical head posture device. For chin-up/down (Figure 6, Top right), data for 3D rotation with chin-up are presented in the upper part of the figure (quadrants I and II), with chin-down in the lower part (quadrants III and IV). When chin-ups were associated with right tilts, and chin-downs were associated with left tilts, outputs of chin-ups/downs were lower than the actual rotations. When chin-ups were associated with left tilts, and chin-downs were associated with right tilts, outputs of chin-ups/downs were nearly identical to the actual rotations. For head tilt rotation (Figure 6, Bottom left), the outputs of associated chin-up/down were close to the actual rotations.

Analysis of the normal subject data for 3D head rotations showed high correlation between angles of mechanical head posture measuring system and angles of digital head posture measuring system for all 3 dimensions. Correlation coefficients were higher than 0.99.

Ninety-five percent limits of repeatability were computed between the 3 tests of all 12 normal subjects using Equation 1. Plots of difference vs mean for 10-degree increments of all 3D movements were created to show these limits of repeatability (Figures 7, Top left and right and Bottom left). As shown in Figure 7, the range of maximum limits of repeatability was found to be less than ±2.5 degrees for head-turns of 10 degrees; less than ±3.0 degrees for 20-degree head-turns; and approximately ±4 degrees for 30-degree head-turns. In Figure 6, the data for head positions of right turn in combination with head tilt and chin-up/down are plotted on the right side of the figure, with left head-turn on the left side. There are 3 sets of repeatability data from 3 tests: Test 1 vs Test 2, Test 3 vs Test 3 and Test 3 vs Test 1. These data were plotted with the same symbols because the testing conditions were identical. For chin-ups/downs, the range of maximum limits of repeatability was found to be less than ±2.5 degrees for 10-degree chin-ups/downs; approximately ±3 degrees for 20-degree chin-ups/downs; and ±4 degrees for 30-degree chin-ups/downs. For head tilts, the range of maximum limits of repeatability was found to be less than ±4.5 degrees for 10-degree tilts; approximately ±6 degrees for 20-degree tilts; and less than ±8 degrees for 30-degree tilts.
DISCUSSION

Most clinicians use simple observation to determine anomalous head posture for clinical use. According to a report from Kim and associates, the range of the error was from 2 degrees to 18 degrees in visual estimation. Granet and associates had a similar observation. For a 30-degree head-turn, examiners estimate varied from 10 degrees to 50 degrees. There have been several methods developed to measure abnormal head posture. Young and Lundström used photographic methods to measure abnormal head posture, but their data analysis was time consuming, and the results were not promptly available. Yang and associates reported using a L3D system consisting of a head mounted laser pointer and a display grid pattern to measure head posture. However, this method requires patients to be very cooperative because translational movements of the head might be displayed on the grid as head rotations. Using an inclinometer and Rustrak Ranger recorder, a portable device was developed to measure 1- or 2-dimensional head position. Because of the portability of the device, it could measure head posture during walking. However, there have been only 2-dimensional measurements reported using such a device. It has also been reported that a cervical range of motion device is a useful device for abnormal head posture measurement. But in clinical practice, reading the small marks of a head position on 3 meters is not as easy when testing young children whose heads move quickly and frequently. Conversely, a digital head posture measuring system can accurately measure the anomalous head posture for children in 3D. The repeatability of the method has been shown to be high as 0.99 for these conditions. For head tilts, when chin-ups were associated with right tilt, and chin-downs were associated with left tilt, output of the digital head posture measuring system for chin-up/downs were lower than the actual rotations. We believe these errors might be caused by inaccurate rotations of the human heads guided with the mechanical head posture measuring device.

Additionally, we fitted a linear mixed effects model to measured chin-up/downs as a function of true chin-up/downs. The results indicate that measured chin-up/down has a nonconstant bias. The bias changes linearly with the size of the rotations. Using this linear relationship, we made a correction for the chin-up/down outputs of greater than 1 standard division. After the correction, the digital head posture measuring system outputs are very close to the true rotations. This implies to us that the measurement errors can be reduced with software correction in further clinical application of the digital head posture measuring system (see Supplemental Appendix available at AJO.com).

The repeatability of the method has been shown to be high. The results of head-turn and chin-up/down outputs of the digital head posture measuring system showed that the range of 95% LoA were less than ±5 degrees, although the head tilt showed a larger range of repeatability, ±8 degrees for the movement of 30 degrees. The reason why the head tilt movements had larger range of repeatability could be partially attributable to reading errors from the protractors.

Measurement of head posture using the digital head posture measuring system is quick and easy, each measurement takes only a few seconds. Multiple tests can be completed within a few minutes. The motion tracker is a small (1.5 × 2 × 9 cm) device that can be mounted on a frame of spectacles (see Figure 2) and used for children.

Taking all results into account, we think the digital head posture measuring system is an acceptable device with high accuracy, repeatability, and validity in measuring head posture in 3D.
REFERENCES

SUPPLEMENTAL APPENDIX

A LINEAR MIXED EFFECTS MODEL WAS USED TO MODEL measured pitch as a function of true pitch. This model included a random intercept to account for subject heterogeneity. A weighting function was included in the model. Observations with larger magnitudes were given less weight. This was necessary because higher magnitude measurements were more imprecise. The weights were estimated as:

\[
\frac{1}{|\text{pitch}|^6}
\]

where \( \delta \) was estimated approximately as 0.771 and “pitch” denotes the true or actual pitch. The function relating the observed measurement to the true measurements was:

\[
\text{measured pitch} = 0.003 + 0.850 \times \text{true pitch}
\]

The 95% confidence interval for the slope was from 0.843 to 0.857 and the 95% confidence interval for the intercept was from -0.146 to 0.151. There was very little subject heterogeneity—the standard deviation of the random intercept was 0.170. The measurement error standard deviation is a function of true pitch:

\[
\sqrt{0.205^2 \times |\text{pitch}|^{2 \times 0.771}}
\]

The results indicate that measured pitch has a nonconstant bias, and the bias changes linearly with size of the rotation.
Biosketch

Dongsheng Yang, PhD, is an Assistant Professor of Ophthalmology and Bioengineering at the University of Pittsburgh and Director of the Laboratory of Ocular Motor Research in the Department of Ophthalmology. Dr Yang has published more than 30 research papers and 2 book chapters in the field of vision research. His research has been supported by National Institute of Health. Dr Yang research interest is focused on ocular motility.
Eric S. Hald is a Senior Bioengineering student at the University of Pittsburgh. He has been a Research Assistant for the past two years in the Laboratory of Ocular Motor Research in Children’s Hospital of Pittsburgh, under the direction of Drs Dongsheng Yang and Richard Hertle. Mr Hald has presented posters at the AAPOS 2007 and ARVO 2008 conferences, detailing his various stages of work with a digital head posture measuring device. He received Fight-For-Sight’s Summer Research Fellowship Grant for Summer 2008 to continue his research in developing a head posture measuring device. His career interests include pediatric and ophthalmologic medicine.