Nintendo Wii Remote Controllers for Head Posture Measurement: Accuracy, Validity, and Reliability of the Infrared Optical Head Tracker

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PURPOSE. To evaluate the accuracy, validity, and reliability of a newly developed infrared optical head tracker (IOHT) using Nintendo Wii remote controllers (WiiMote; Nintendo Co. Ltd., Kyoto, Japan) for measurement of the angle of head posture.

METHODS. The IOHT consists of two infrared (IR) receivers (WiiMote) that are fixed to a mechanical frame and connected to a monitoring computer via a Bluetooth communication channel and an IR beacon that consists of four IR light-emitting diodes (LEDs). With the use of the Cervical Range of Motion (CROM; Performance Attainment Associates, St. Paul, MN) as a reference, one- and three-dimensional (1- and 3-D) head postures of 20 normal adult subjects (20–37 years of age; 9 women and 11 men) were recorded with the IOHT.

RESULTS. In comparison with the data from the CROM, the IOHT-derived results showed high consistency. The measurements of 1- and 3-D positions of the human head with the IOHT were very close to those of the CROM. The correlation coefficients of 1- and 3-D positions between the IOHT and the CROM were more than 0.99 and 0.96 (P < 0.05, Pearson’s correlation test), respectively. Reliability tests of the IOHT for the normal adult subjects for 1- and 3-D positions of the human head had 95% limits of agreement angles of approximately ±4.5° and ±8.0°, respectively.

CONCLUSIONS. The IOHT showed strong concordance with the CROM and relatively good test–retest reliability, thus proving its validity and reliability as a head-posture–measuring device.

Considering its high performance, ease of use, and low cost, the IOHT has the potential to be widely used as a head-posture-measuring device in clinical practice. (Invest Ophthalmol Vis Sci. 2012;53:1388–1396) DOI:10.1167/iovs.11-8329

A nomalous head posture, or torticollis, occurs in approximately 1.3% of children.1 The etiologic factors that are responsible for this condition include ocular, orthopedic, and neurologic abnormalities.2–4 For example, patients with superior oblique palsy predominantly manifest a head tilt, whereas patients with nystagmus or Duane’s retraction syndrome manifest a face turn.2 Several studies showed that children with ocular torticollis may benefit from early diagnosis and treatment. Patients experienced improvement in their visual acuity, and permanent musculoskeletal problems such as facial asymmetry were prevented to some degree.3–4

Accurate measurement of the angle of anomalous head posture is crucial for evaluating disease progression and determining surgical plans in patients with ocular torticollis. Recently, several useful instruments in measuring anomalous head posture have emerged. Kushner5 demonstrated that the Cervical Range of Motion system (CROM; Performance Attainment Associates, St. Paul, MN) is useful for anomalous head posture measurement. However, a reliable measurement of head posture during minute movements remains a difficult task in clinical practice.

Hald et al.6 reported the accuracy and reliability of a digital head-posture-measuring system incorporating a motion tracker (InterSense, Inc., Billerica, MA). With this system, the head posture of young patients was accurately measured through digital assessment, which allows for prompt reporting and error-free archiving of the results as well. However, this motion tracker is expensive for widespread clinical application (>$2000 U.S.).

In this study, we developed a high-performance, simple, and inexpensive digital head-posture-measuring device—the infrared optical head tracker (IOHT)—that automatically measures and records the angle of head posture in real time using two Nintendo Wii remote controllers (WiiMote; Nintendo Co. Ltd., Kyoto, Japan). The WiiMote provides an inexpensive alternative for measurement of head posture. It includes a three-axis accelerometer, an infrared (IR) camera sensor, and Bluetooth connectivity (Bluetooth SIG, Inc., Kirkland, WA). Such a rich set of features has inspired several projects that repurposed the WiiMote for non-Wii-related applications.7 For this study, the IR camera and Bluetooth connectivity were used.

In the present study, we used the newly developed IOHT to measure the head posture of normal adult subjects in one- and three-dimensions (1- and 3-D) and evaluated its accuracy, validity, and reliability in comparison to the CROM device, which...
is considered the gold standard for measurement of head posture.

**Subjects and Methods**

Twenty adult subjects (20–37 years of age; 9 women and 11 men) with normal head posture and vision were studied. The study protocol complied with the Declaration of Helsinki and was approved by the Institutional Review Board (IRB) of Seoul National University Bundang Hospital (SNUBH) (IRB approval B-0907/080-007). Informed consent was obtained from all subjects after the details of the study were explained.

**Infrared Optical Head Tracker**

*The IOHT with Wii Remote Controller.* The IOHT setup is composed of two WiiMotes that are fixed to a mechanical frame and connected to a monitoring computer via a Bluetooth communication channel, an IR beacon that consists of four IR (950 nm) light-emitting diodes (LEDs), and other related electronic subparts (Figs. 1A, 1B). The mechanical frame is manufactured to adjust the height of the vertical rod, the horizontal rotation of the vertical rod, the horizontal distance between the two WiiMotes, the vertical angle of the horizontal plate, and the relative horizontal angle between the two WiiMotes (Fig. 1C). Each WiiMote independently detects the relative 2D positional information of the IR beacon and transfers the information to the monitoring computer continuously via a Bluetooth USB dongle (BT-0001; Billionton Systems Inc., Hsinchu, China). The two 2-D positional information is then integrated by a stereo matching technique that calculates the 3-D position of the IR beacon. Using this real-time 3D positional information, the subject’s head posture is represented by three angles: head turn, $\phi_h$; cervical flexion/extension, $\phi_c$; and lateral tilt, $\phi_l$, as shown in equation 1.

\[
\text{Head Posture}(\phi_h, \phi_c, \phi_l) = \text{Rot}(h, \phi_h)\text{Rot}(c, \phi_c)\text{Rot}(l, \phi_l)
\]

where $\text{Rot}$, $C$, and $S$ represent the rotation matrix, cosine function, and sine function, respectively. By solving this matrix calculation, each targeted angle value can be obtained as shown in equation 2:

\[
\begin{align*}
\phi_h &= \text{ATAN}2(l_1, l_2) \\
\phi_c &= \text{ATAN}2(-l_1, -1) \\
\phi_l &= \text{ATAN}2(-h_1, C_2, C_1, C_0)
\end{align*}
\]

where $\text{ATAN}2$ represents the trigonometric function arc-tangent 2. Overall, mathematical procedures were performed by custom software that was programmed in Visual C++ (Microsoft Visual Studio version 2008; Microsoft Inc., Redmond, WA).

**Initial Setting of Virtual 3-D Space.** To measure the subject’s head posture using the IOHT, we set a virtual 3-D space around the subject’s head. An IR LED-mounted cubic box (Withrobot Co., Ltd., Seoul, Korea) that contains 16 IR LEDs arranged in a $4 \times 4$ matrix (Fig. 2A) was placed at the position of the subject’s head in front of the mechanical frame (Fig. 2A). The WiiMotes were turned on and connected to the monitoring computer via the Bluetooth dongle. IR LEDs mounted on the left and right sides of the LED box were then sequentially turned on, and the two WiiMotes simultaneously detected and registered the position of the 32 IR LEDs (Fig. 2C). Thereafter, the custom software set virtual 3-D coordinates around the cubic box by a stereo-matching technique.

**Measurement of Head Posture with the IOHT.** Once the virtual 3-D space was set, the LED box was removed; the subject wearing the IR beacon on his or her forehead sat in front of the mechanical frame, and the system began to operate. From this point, resetting of virtual space was not necessary, unless the relative position between the WiiMotes and the mechanical frame was changed. The positions remained the same because the virtual 3-D space set by IOHT is wide enough to detect and measure the signals coming from the foreheads of subjects of all heights, except for subjects of short stature. In such cases, the mechanical frame would be lowered to match the gaze, and the WiiMotes are able to reset the 3-D virtual space and continue to give accurate measurements of the head posture of those children.

In this study, the distance between the frame and the subject was adjusted to be approximately 50 cm during measurement. In the first operation, a trained ophthalmologist manually moved the subject’s head to a straight and unbiased head posture by using the visual estimation, which was confirmed by CROM as the zero position. By clicking a zero button on the custom software, the zero position was saved as a reference posture that represented all zero angles, and the 1- and 3-D positions of the center of the IR beacon were detected in real time (30 Hz) and in high spatial resolution (1 nm). On the basis of this reference position and the real-time position information, the various angle parameters (head turn, cervical flexion/extension, and lateral tilt) that represent the head posture were calculated and displayed on the computer screen (Fig. 1D).
The CROM. This device is a commercially available instrument used for the measurement of head posture. The CROM device consists of three direction indicators similar to those of a goniometer: one magnetic (influenced by the magnetic yoke around the neck) and two gravity-driven indicators. The side indicator measures cervical flexion and extension, and the front indicator measures lateral tilt. The transverse indicator, mounted on top of the CROM device, is a goniometer that measures head turn.

Procedures

Accuracy and Precision Test of the IOHT in 1-D Positions of IR Beacon. To evaluate the accuracy and precision of IOHT, we first compared the angle calculated by IOHT with measurements from a commercialized goniometer (Slant Level TL-100; Sangbo Co. Ltd., Seoul, Korea) and a protractor (AM-707; Songhwa Co. Ltd., Asan, Korea) for turn, flexion/extension, and tilt motions (Fig. 3). The 1-D positions of IR beacon ranged from $-40^\circ$ (right turn) to $+40^\circ$ (left turn), from $-40^\circ$ (flexion) to $+40^\circ$ (extension), and from $-40^\circ$ (right tilt) to $+40^\circ$ (left tilt). The movement of the IR beacon was adjusted and recorded in increments of $10^\circ$ for all motions. Each of the measured angle values were rounded off to the nearest integer, and each position was measured 15 times to obtain the mean angular difference and the standard deviation of the IOHT.

Validity and Reliability Test of the IOHT in 1-D Positions of the Human Head. To observe the concordance of the measurements between the IOHT and the CROM and to evaluate the test-retest reliability of the IOHT, we attached the IR beacon to the upside of the front indicator of the CROM (Figs. 4A, 4B). To measure head posture, we set a virtual space in front of the mechanical frame and...
positioned the normal adult subject wearing the IR beacon-attached CROM at a distance of 50 cm in front of the WiiMotes and the mechanical frame of the IOHT (Fig. 4C). The 1-D positions of the human head ranged from \(-40^\circ\) (right turn) to \(+40^\circ\) (left turn), from \(-40^\circ\) (flexion) to \(+40^\circ\) (extension), and from \(-40^\circ\) (right tilt) to \(+40^\circ\) (left tilt) for head turn, cervical flexion/extension, and lateral tilt, respectively. The movement of the head was adjusted and recorded in increments of 10° for all movements. The measured angle values were rounded off to the nearest integer and were measured two times per subject for evaluation of the test–retest reliability of the IOHT.

Validity and Reliability Test of the IOHT in 3-D Positions of the Human Head. The equipment and settings were the same as those for the measurement of the 1-D position. The difference was that the head of the subject was positioned with respect to head turn, cervical flexion/extension, and lateral tilt of up to 30° in each quadrant, to account for all possible anomalous head positions in clinical cases. We measured the changes in those parameters when the position of the head was shifted from an initial reference point to a predefined 3-D position. The angle measurements were rounded off to the nearest integer and were obtained two times in each subject, for evaluation of the test–retest reliability of the IOHT, making a total of 48 head positions in four quadrants.

Data Analysis

Graphic and statistical analyses of the head position data from the subjects were performed. Correlation coefficients for each head position were calculated over the range of angles measured. Differences between test and retest IOHT data were calculated for each subject. The 95% limits of agreement were calculated and are represented in Bland-Altman plots. Results were interpreted as statistically significant at \(P < 0.05\) (GraphPad Prism 5; GraphPad Software, San Diego, CA).

RESULTS

Accuracy and Precision of the IOHT in 1-D Positions

Accuracy and precision test of the measurements of IOHT in comparison with a goniometer (and a protractor) are shown in Figure 5. For IR beacon turn, the mean angular differences between the IOHT and goniometer ranged from 0.13° to 0.47°, IR beacon flexion/extension from 0.07° to 1.35°, and IR beacon tilt from 0.07° to 0.87°. Precision represents the
Validity of the IOHT in 1-D Positions of the Human Head

For all three kinds of head movements, the relationship between the results from the IOHT and CROM was linear and correlated highly ($r > 0.99$, $P < 0.05$; Pearson’s correlation test). For head turn (Fig. 6A), the correlation coefficient between the IOHT and the CROM was $r = 0.992$ ($P < 0.001$). The mean angular difference and SD of outputs at each position varied from $0.27^\circ$ to $1.17^\circ$ and $1.31^\circ$ to $2.57^\circ$, respectively. For cervical flexion/extension (Fig. 6B), the correlation coefficient was $r = 0.992$ ($P < 0.001$). The mean angular difference and SD of outputs at each position varied from $0.88^\circ$ to $1.73^\circ$ and $1.85^\circ$ to $2.69^\circ$, respectively. For lateral tilt (Fig. 6C), the correlation coefficient was $r = 0.993$ ($P < 0.001$). The mean angular difference and SD of outputs at each position varied from $0.17^\circ$ to $2.55^\circ$ and $1.50^\circ$ to $2.69^\circ$, respectively.

Reliability of the IOHT in 1-D Positions of Human Head

The 95% limits of agreement were computed between the two tests of 20 normal adult subjects (Fig. 7). As shown, the range of 95% limits of agreement was $-4.23^\circ$ to $+3.90^\circ$ for $10^\circ$ of 1-D head postures, $-4.65^\circ$ to $+4.05^\circ$ for $20^\circ$, and $-4.53^\circ$ to $+4.01^\circ$ for $30^\circ$.

Validity of the IOHT in 3-D Positions of the Human Head

The head position data were plotted in four quadrants in accordance with the direction of head rotation (Fig. 8). Analysis of the normal adult subject data for 3-D head rotations showed high correlation between the IOHT and the CROM for all three head postures ($r > 0.96$, $P < 0.05$; Pearson’s correlation test). For head turn (Fig. 8A), data for combined 3-D positions with right turn are displayed in quadrants 2 and 3, with left turn in quadrants 1 and 4. The mean angular difference and standard deviation of outputs at each position varied from $0^\circ$ to $3.44^\circ$ and from $2.51^\circ$ to $4.39^\circ$, respectively. The correlation coefficient between the IOHT and the CROM was $r = 0.968$ ($P < 0.001$). For cervical flexion/extension (Fig. 8B), data for 3-D positions with cervical extension are presented in quadrants 1 and 2, with cervical flexion in quadrants 3 and 4. The mean angular difference and standard deviation of outputs at each position varied from $0.22^\circ$ to $3.26^\circ$ and from $2.32^\circ$ to $4.42^\circ$, respectively. The correlation coefficient between the IOHT and the CROM was $r = 0.973$ ($P < 0.001$). For lateral tilt rotation (Fig. 8C), data for 3-D positions with right head tilt are represented by the solid line and left head tilt by the dotted line. The mean angular difference and SD of outputs at each position varied from $0.06^\circ$ to $3.26^\circ$ and from $2.04^\circ$ to $4.48^\circ$, respectively. The correlation coefficient between the IOHT and the CROM was $r = 0.961$ ($P < 0.001$).

Reliability of IOHT in 3-D Positions of Human Head

The 95% limits of agreement were computed between the two tests of 20 normal adult subjects (Fig. 9). The range of 95% limits of agreement was $-6.52^\circ$ to $+7.18^\circ$ for $10^\circ$ of 3-D head postures, $-7.43^\circ$ to $+7.14^\circ$ for $20^\circ$ (Fig. 9B), and $-8.13^\circ$ to $+8.29^\circ$ for $30^\circ$ (Fig. 9C).

**DISCUSSION**

A few studies have measured head posture by analog methods (inclinometric11 or photographic12,13) from the view of orthodontics or orthopedics. Unfortunately, these methods are not...
applicable in real-time clinical practice. Other studies\textsuperscript{8,14–16} demonstrated good validity and reliability of CROM in various head positions. Kushner\textsuperscript{5} reported that the CROM is useful in evaluating anomalous head posture; however, in clinical practice, it is difficult to obtain reliable, consistent data for the three indicators of the CROM when testing patients, especially

**FIGURE 6.** Results of validity tests of the IOHT compared with the CROM for 1-D positions of the human head in 20 normal adult subjects. The relationship between outputs of the IOHT and the CROM correlated highly in all three head postures ($r > 0.99$; $P < 0.05$). The mean angular difference and standard deviation at each position was, respectively, 0.27$^\circ$ to 1.17$^\circ$ and 1.31$^\circ$ to 2.37$^\circ$ for head turn (A), 0.08$^\circ$ to 1.73$^\circ$ and 0.17$^\circ$ to 2.55$^\circ$ for cervical flexion/extension (F/E) (B), and 0.17$^\circ$ to 2.69$^\circ$ for lateral tilt (C). deg, degree.

**FIGURE 7.** Bland-Altman plots showing test-retest reliability of the IOHT in 1-D positions of the human head between tests 1 and 2 in 20 normal adult subjects. (A) For 10$^\circ$ of 1-D head postures, the range of 95% limits of agreement was from $-4.23^\circ$ to $+3.90^\circ$; (B) 20$^\circ$, from $-4.65^\circ$ to $+4.05^\circ$, and (C) 30$^\circ$, from $-4.53^\circ$ to $+4.01^\circ$. Upper and lower dotted lines: 95% limits of agreement with 95% confidence intervals. deg, degree.
children, whose heads move constantly. In this respect, an ideal head-posture-measuring device would require little to no patient cooperation and at the same time would gather reliable data.

Recently, digital head-posture-measuring systems using electronic devices, such as motion trackers, have been developed to measure real-time head movement automatically and quantitatively. Hald et al.6 reported the validity and reliability of a digital head-posture-measuring device using InterSense; however, this system requires expensive electronic devices (> $2000 U.S.). In a previous study, Lee et al.17 reported that the WiiMote can offer 2-D motion tracking in a compact and inexpensive package, and in this study, we made a relatively low-cost (approximately $700 U.S.), but accurate, 3-D head-posture-measuring device incorporating two WiiMotes. The system showed good validity and reliability in normal adult volunteers.

The validity of the IOHT was evaluated by using the CROM as a reference standard in normal adult subjects. In 1-D head position measurements, the outputs of IOHT of 1-D head positions were close to those of the CROM (Fig. 6). The relationship between outputs of IOHT and CROM correlated highly ($r > 0.99; P < 0.05$), the mean angular difference between the two devices was <3.0° and standard deviations ranged from 1.0° to 3.0°. On the other hand, in 3-D head position measurements, the strength of correlation between the IOHT and CROM was less than that in the 1-D situations ($r > 0.96; P < 0.05$). The mean angular difference between the two devices was less than 3.5°, and standard deviations ranged from 2.0° to 4.5° (Fig. 8). A possible explanation for this slight deviation could be the varying CROM-guided rotations of the subject’s head and that the second hands of the CROM indicators are prone to hitting the glass during large-angle 3-D movements, such as 20° turn, 20° flexion, and 20° lateral tilt. Therefore, measurement of the 3-D position becomes less and less accurate as the movement angle increases. Last, simultaneous reading of the three CROM indicators is hindered by the continuous slight movements of the subject’s head.

In our study of test–retest reliability using IOHT, the range of 95% limits of agreement of 3-D head positions was about ±7.0° for 10° and 20° of head postures and approximately ±8.0° for 30° of head postures (Fig. 9), a value that is slightly larger than that of Hald’s device.6 In our study the range of 95% limits of agreement of head turn and cervical flexion/extension outputs were less than ±5.0°, although the lateral tilt showed a larger range of reliability: ±8.0° for a movement of 30°. As mentioned earlier, we think that this difference between the two devices in 3-D position measurements could be due to some structural deficiencies of the CROM—the aforementioned second-hands problem during large-angle 3-D movements and the difficulty in simultaneously reading the three CROM indicators—which may have brought about the larger-than-ideal differences in the measurement.

The main strength of our study is the development of a novel digital head-posture-measuring device, IOHT, and its high correlation with a well-established head-posture-measuring method, CROM. The IOHT is a real-time three degree-of-freedom motion-tracking device with high spatiotemporal resolution (temporal resolution of 30 Hz and spatial resolution of 1 mm). It is able to detect the position of the subject 30 times per second with high accuracy. In addition, the measurements of IOHT are not affected by the earth’s magnetic force: the subject can sit facing any direction, and the IOHT can obtain accurate data from his or her head posture in reference to its zero position, whereas with the CROM, the subject has to sit facing true magnetic north or use an additional magnet yoke to prevent interference from the earth’s magnetic field. Moreover, IOHT uses cheaper, smaller, and lighter commercialized electronic elements (WiiMotes and IR beacon) instead of costly head-posture-measuring devices (InterSense or Polhemus, Colchester, VT). The total manufacturing cost of the prototype IOHT was approximately $700 U.S. (approximately $200 U.S. for electronic
parts such as the IR beacon, LED box, WiiMotes, and Bluetooth dongle and $500 U.S. for the mechanical frame). Among them, the mechanical frame was the most expensive because it had to be custom made of metal. Nevertheless, the manufacturing cost of the mechanical frame can be reduced if the design is simplified and more inexpensive material such as plastic is used instead of metal. Finally, in the evaluation of incomitant strabismus and diplopia, the boundaries of the 3-D range of single binocular vision at distance fixation could be displayed by data processing using IOHT. To our knowledge, there is no current device that is able to measure the range of motion of single binocular vision at distance. The Goldmann perimeter (GP) is the clinical standard for quantifying the range of motion of single binocular vision at near fixation, and some researchers have used the CROM. However, the GP and CROM cannot measure the range of single binocular vision at distance as with the IOHT.

Despite these advantages, the IOHT has some limitations. First, because of its fast sampling rate (30 Hz), the ability of real-time measurement by the IOHT can confuse the examiner in a clinical situation in which subjects’ heads are prone to trembling or slight movements, which would be represented as a rapidly changing angle. This problem was particularly prominent in uncooperative subjects, and we assumed that it would be the same in children. To overcome this disadvantage and to facilitate clinical application, we introduced a moving-average filter and a finite impulse response (FIR) filter that can obtain the average of all the data measured in one second. Second, the measurable angles of IOHT are limited to ±40° because WiiMote needs to maintain a line of sight with the LEDs. In most cases, such limitation is dismissible because

the degree of anomalous head posture is usually less than ±40°. However, this may affect the result in severe cases of anomalous head posture. Third, the necessity of setting the virtual 3-D space before measurement can be seen as a weakness compared to the CROM or InterSense. Nevertheless, the setting of virtual space is very simple, and no further setting is needed unless the relative position of the WiiMotes and the mechanical frame is changed, which is rarely necessary to change positions because of the wideness of the virtual 3-D space set by the IOHT. Therefore, we think that the need for setting the virtual space will not be a serious problem in most clinical practices. Last, we did not examine the validity and reliability of the IOHT in actual patients with anomalous head posture. Nevertheless, the validity and efficacy of the IOHT was reliably demonstrated through this present study, and since SNUBH has a rich pool of patients with anomalous head posture, a clinical study of the patients will follow soon.

To the best of our knowledge, the IOHT is the first 3-D head-posture-measuring system for application in clinical diagnosis that uses the Nintendo WiiMote. In this study, the IOHT showed strong concordance with the CROM and relatively good test-retest reliability, thus proving its validity and reliability as a head-posture-measuring device. Considering its high performance, ease of use, and low cost, we believe the IOHT has the potential to be widely used as a head-posture-measuring device in clinical practice.

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