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A new tool for assessing head movements and postural sway in children

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Abstract Current methods of measuring gross motor abilities in children involve either high-cost specialist apparatus that is unsuitable for use in schools, or low-cost but nonoptimal observational measures. We describe the development of a low-cost system that is capable of providing high-quality objective data for the measurement of head movements and postural sway. This system is based on off-the-shelf components available for the Nintendo Wii: (1) The infrared cameras in a pair of WiiMotes are used to track head movements by resolving the position of infrared-emitting diodes in three dimensions, and (2) center-of-pressure data are captured using the WiiFit Balance board. This allows the assessment of children in school settings, and thus provides a mechanism for identifying children with neurological problems affecting posture. In order to test the utility of the system, we installed the apparatus in two schools to determine whether we could collect meaningful data on hundreds of children in a short time period. The system was successfully deployed in each school over a week, and data were collected on all of the children within the school buildings at the time of testing ($N = 269$). The data showed reliable effects of age and viewing condition, as predicted from previous small-scale studies that had used specialist apparatus to measure childhood posture. Thus, our system has the potential to allow screening of children for gross postural deficits in a manner that has never previously been possible. It follows that our system opens up the possibility of conducting large-scale behavioral studies concerning the development of posture.

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One of the critical motor milestones in a child's developmental progression is the ability to stand upright without external support. A failure to acquire this fundamental skill has a deleterious effect on an individual, as seen in children with severe cerebral palsy (Saavedra, Woollacott, & van Donkelaar, 2010). The ability to stand upright is an important marker of adequate motor development but young children who show this ability still lack the exquisite levels of postural control evidenced by neurologically intact adults (Schärli, Keller, Lorenzetti, Murer, & van de Langenberg, 2013). Thus, childhood development is associated with the gradual refinement of postural control mechanisms. Nevertheless, not all children manage to develop the normal ability to maintain balance in challenging situations. The consequences of reduced postural control are profound and have a marked impact on a child's education and social development (Sugden, 1992).

A deficit in postural control has a direct influence on a number of activities of daily living (e.g., tying shoelaces when standing). For this reason, the measurement of postural stability is considered central to a thorough assessment of an individual's motor status (Sugden, 1992). Postural control deficits also impact on an individual's ability to hold the head steady (Pozzo, Berthoz, & Lefort, 1990)—and this is problematic, since a stable head is needed to provide accurate visual information for the control of action (Lord & Menz, 2000; Stahl, 1999). Excessive head movements are likely to make it more difficult to control posture, creating a catch-22 situation for individuals with such motor deficits (Assaiante & Amblard, 1995). It follows that an individual with fundamental deficits in postural control will have difficulties in developing manual abilities (because a stable platform and head is required to generate skilled hand movements (Berrigan, Simoneau, Martin, & Teasdale, 2006). These observations explain why excessive head movements are associated with cerebral palsy (Saavedra et al., 2010). It can be seen that the measurement of postural stability and head movement plays an important role in the identification and assessment of developmental problems in children. Unfortunately, it is hard to find suitable apparatus to provide such measurements in school settings.

Culmer, Levesley, Mon-Williams, and Williams (2009) described a system (the Kinematic Assessment Tool (KAT)) capable of providing objective data on a range of visuo-manual tasks. The Kinematic Assessment Tool offers the possibility of obtaining powerful measures of an individual's manual motor skills with the ease and convenience of traditional "paper-and-pen" tests. It is therefore unsurprising that the Kinematic Assessment Tool has been deployed in a large scale cohort study that is attempting to understand the factors related to maternal and child health that can impact negatively on a child's educational and health development (www.borninbradford.nhs.uk). The success of the KAT system is witnessed by the fact that it has been successfully used to test over 1,700 children in the past six months as part of the Born in Bradford (BiB) project (with another 12,000 children due to be tested over the next three years). The KAT system provides useful data regarding a child's fine motor skills but it does not assess an individual's gross motor abilities. It would be desirable, therefore, to test the postural stability of children as well as measure their manual skills in developmental studies (such as the BiB project). The difficulty with incorporating tests of gross motor skills is that no low-cost option is available that provides the quality of information equivalent to the data generated by the Kinematic Assessment Tool. The traditional method of assessing postural stability relies on standardized test batteries such as the Movement Assessment Battery for Children (MABC; Henderson, Sugden, & Barnett, 1992). The MABC is a useful tool and has the advantage of being relatively low cost (once the price of the test has been paid). Nevertheless, the MABC requires skilled practitioners (e.g., qualified psychologists or physiotherapists) to administer and is time consuming. Moreover, the test relies on someone observing a child and timing their ability to maintain a given posture—and this approach introduces problems. It seems reasonable to suppose that the best measures of postural stability involve a child adopting a natural standing position but the limitations of observational techniques means that the MABC requires the children to stand (for example) on one leg whilst the examiner observes how long this posture can be maintained. This makes testing more difficult and can be stressful for children who are aware that they are being "tested" (and this might invoke anxiety that will add noise to the measurement process). The alternative to using "pen-and-paper" batteries such as the MABC is the deployment of electronic measurement equipment such as force platforms. A wide range of commercially available force platforms can provide useful measures related to changes in the center of gravity of an individual standing on the force plate. These systems are typically located in research laboratories and have provided great insights into the nature of postural motor control in humans. The quality of the data supplied by these systems is not in doubt but they are expensive.

We therefore set out to design a system that had the portability and low cost of a standardized test battery but that could supply data of the quality normally collected within research laboratories rather than school settings. One low cost device that recently has become popular for measuring posture is the Nintendo (Nintendo, Kyoto, Japan) WiiFit board. It has been shown that this device is an adequate substitute for force platforms in the measurement of postural sway (Clark et al., 2010; Young, Ferguson, Brault, & Craig, 2011). Nevertheless, some factors are specific to the application of the system in children. The lower fidelity of the hardware, coupled with a lower signal/noise ratio (owing to the low mass of the participants and the nature of the measured tasks) makes between-group identification of postural differences difficult. These engineering challenges were met via the development of filtering and analysis techniques. We also set out to design a system that could simultaneously measure head movements. Our rationale was that a major goal of the human postural system is to ensure the stability of the head (Pozzo et al., 1990) so that stable visual information can be used to guide skillful interactions with the world. On these grounds it was conjectured that measurements of head stability would provide an index of an individual's ability to maintain stable posture. Thus, movements of the head during stationary stance might be a useful measure when trying to identify individuals with movement problems (perhaps in conjunction with measures of the Centre of Pressure [COP]). Moreover, data on how the head moves during stationary stance might shed light on the nature of postural motor control. This might be particularly interesting when exploring tasks that require head movements (e.g., visual or manual tasks in which moving targets need to be tracked for successful performance; Schärli, van de Langenberg, Murer, & Müller, 2012).

Some commercial systems are available that can provide data on head movements. For example, inertial motion capture systems have been developed to incorporate micro-electronic accelerometers and gyroscopes and can be made small enough to be worn on the head (Zhou & Hu, 2008). These systems typically use three orthogonal accelerometers to specify an acceleration vector that is transformed into a consistent (typically gravitational) frame of reference using the data from three gyroscopes. However, the data provided by inertial sensors may not be optimal for measuring head movements. The difficulty is that rotational head movements caused by sway around the ankle subtend only a few degrees and therefore the signal/noise ratio in this measurement is low, leading to inaccurate measurement of postural movement. Integrating the accelerometer signals twice to obtain head displacement would enable crude calculation of positional data but low signal/noise ratio and twofold integration again yields unreliable results. An alternative approach is to use a magnetic motion capture system (such as the Ascension “Flock of Birds” system) that derives a 3-D position from a magnetic field in three orthogonal planes (Welch & Foxlin, 2002). These systems have the advantage of being light and compact so they can be readily placed on the head (though the cables can interfere with head movement). There are two disadvantages with these systems. First, they are expensive and require a degree of technical competence in the user. Second, the systems are sensitive to ferrous or conductive objects as these disturb the magnetic field within which the sensors operate. The system can be calibrated to account for simple static ferrous objects but in less controlled environments (e.g., schools) this is impractical. Finally, clinical motion capture equipment is extremely effective in accurately measuring the spatial position of reflective markers, attached to key anatomical landmarks, across a wide measurement volume, typically achieving a submillimeter measurement error over 2 m^3 measurement volumes (Richards, 1999). One of the principal advantages of the optical motion capture systems is their ability to operate wirelessly, which reduces measurement interference and reduces the risk of accidental damage of the equipment. In addition, some systems are portable and can be calibrated in-situ to varying degrees of resolution requirements. The main disadvantages of using equipment of this type outside of the laboratory setting is that the equipment is complex to set up, costly and requires a relatively large amount of space in which to operate. The calibration of the portable optical motion capture systems is also sensitive to accidental shifts in camera position during testing, something that is difficult to guarantee when testing children in a relatively uncontrolled environment.

We therefore sought to design a low cost wireless system that could provide accurate data on head movements concurrently with data collection involving the Nintendo Wii Fit board. We then tested the system we developed in two UK primary schools to ensure that the system could be deployed easily by nonspecialist staff and could generate accurate, robust and clinically relevant data.

Description of the head-tracking system

Recent research has seen the use of consumer electronics as a platform for human movement measurement in the form of the Nintendo Wii, and specifically its controller, the WiiMote. Broad similarities between the WiiMote technology and clinical-based motion capture systems have resulted in the development of a number of applications of rudimentary stereo-vision systems based on the WiiMote controllers. The WiiMote comprises an infrared (IR) camera capable of resolving IR point sources in the 800 to 950 nm wavelength range and relaying only the pixel coordinates (at a resolution of 1,024 × 768 pixels) of up to four IR point sources. In addition, the WiiMote has two properties that made it particularly amenable to wide-scale deployment outside the laboratory environment: (1) It uses wireless Bluetooth communication and is battery powered, allowing for flexible, cable-free placement, and (2) it is of relatively low cost (c. $20/£15), ensuring that the methods developed here have scalability in their application. Nevertheless, if the low-cost components failed to have the degree of precision needed, their cost would be irrelevant, so a suitable calibration process capable of compensating for the comparatively low optical quality of the WiiMote cameras was required.

The measurement resolution and accuracy of any optical motion capture system is proportional to the size of the measured volume. Previous systems developed using the WiiMote have been created as a platform for human–computer interaction (Modroño et al., 2011; Scherfgen & Herpers, 2009). Owing to their necessarily large measurement volume (to capture the extent of large movements), the accuracy of WiiMote-derived systems, although comparable to much more expensive equipment, is correspondingly low (Hay, Newman, & Harle, 2008). The measurement of head movement in quiet standing would require a small measurement volume. By exploiting the relationship between measured volume and accuracy, the WiiMote-derived motion capture system could be optimized for small measurement volumes, similar in principle to how clinical-grade equipment can be reconfigured to measure small volumes at sub-100 μm accuracies (Windolf, Götzen, & Morlock, 2008). Furthermore, we felt that the accuracy of the measurement could be increased sufficiently to enable sensitive detection of head movements and changes across the developmental trajectory.

In addition to the accuracy requirements of the equipment, it was important to consider that this system would be operated by nonexpert users. To achieve this, a stereo-vision module was developed that integrated two precalibrated WiiMote controllers into a tripod-mounted housing that connected wirelessly to a host computer with error checking software and a graphical user interface. This simplified system facilitated deployment and operation outside of the laboratory setting and avoided the requirement to calibrate the system in-situ.

Calibration

Error in locating a triangulated point in space can arise from two specific optical properties of the stereo system: errors resulting from the distorting effect of the lenses on the observed image (intrinsic errors), and errors that occur due to inaccurate knowledge of the position and orientation of the cameras with respect to each other (extrinsic errors). Thus, improvement in the accuracy of determining the triangulated position is dependent on being able to correct for the optical distortions and also accurately calculating the position and orientation of each camera through *intrinsic* and *extrinsic* calibration of the system. This study uses the widely used camera calibration toolbox (Bouget, 1999) to identify, and compensate for lens distortions. To calculate the internal parameters of the camera, this toolbox uses the method proposed by Zhang (1999), in which an image of a checkerboard calibration pattern is taken in a range of orientations and positions with respect to the camera. Computer vision software identifies point coordinates at the corners and intersections of the checkerboard pattern. Disparities between the point locations observed on the distorted image and those anticipated if the camera distortions were not present (as determined from the geometry of the grid pattern) were calculated, and input as errors into an optimization model. The model determines the lens distortion (radial, tangential and skew), focal length, image principal point, and the pixel distortion that best describes the grid distortion observed in the camera image, resulting in a matrix of intrinsic camera properties that can then be used to correct for the distortions.

For stereo calibration, an image of the calibration grid can be taken in both cameras, and the same computer vision technique can then identify corresponding points between the images (after the images in each camera are corrected for lens distortion). Differences in the position of corresponding points between camera images then serve as inputs into a stereo calibration model. The optimization determines the relative translation and orientation of the cameras that best describe the observed point location differences between the images. Thus, with the relative translation and orientation of the cameras known, a straightforward triangulation calculation can be performed using the pixel coordinates from both images coupled with the known optical properties of the stereo vision system to calculate the three-dimensional position of the point in space.

Implementation of the original grid-based calibration toolbox routine was not suitable for deriving the WiiMote camera properties, since there was no access to the camera image. A grid could theoretically be reconstructed using a series of IR diodes in a planar pattern, but the WiiMote is only capable of tracking up to four IR diodes at a time. An alternative could be to sequentially illuminate four IR diodes that are part of a planar grid pattern. This could build up a patchwork grid pattern of coordinates that, when recombined into a single image, would provide a calibration grid reference serving either as an input into a calibration routine or as a method of establishing a direct mapping between the pixel and three-dimensional coordinates (Kim et al., 2012). We used the more elegant solution of a simple four-point calibration board and used the four point sources as “corner points” of a grid with no intermediate grid points. By using a large number of these corner images, sufficient error inputs were observed for the calibration optimization model of lens distortion properties to converge. The original grid-based calibration routine was therefore modified to use data in the form presented by Bakstein and Halíř (2000). Through optimization, the calibration software solved an internal camera model developed by Heikkila and Silven (1997), which comprised parameters for lens distortion (radial, tangential and skew), focal length, image principal point and pixel distortion. With the optical properties of the lenses determined, the same calibration board was then used as a basis for the stereo calibration technique, in which the optimization routine was modified to accommodate information from a large number of board images. Convergence of the stereo calibration optimization yielded the relative positions and rotations of the cameras that best described positional (pixel coordinate) differences of corresponding points between camera images.

Calibration for intrinsic camera properties A calibration image capture sequence acquired snapshots of a four-IR-diode calibration board powered using a 9 V battery. The four IR diodes were placed in a 150 mm square formation. The calibration required the capture of between 250 and 350 “images” (2-D coordinates of the IR diodes in the camera image plane) of the stationary calibration board in a range of orientations, distances and positions across the image to enable successful convergence of the calibration optimization routine. The calibration images were captured at 0.5 Hz intervals. Three calibrations were performed on each camera in the stereo pair, and a script contained within the calibration toolbox was used that was able to combine the separate calibrations to improve accuracy of the overall model solution. For each image in the calibration, a parameter error was calculated for each parameter in the optimization model. A range of uncertainty for each calibration parameter could then be computed as the calculated calibration parameter value +/- three times the standard deviation of this error (over all images in the calibration). If a value of zero fell within this range the calibration was discarded and repeated, since this would be indicative of a failed optimization.

Calibration for extrinsic camera properties The two WiiMotes were integrated and fixed to a stereo-vision housing in order to facilitate ease of transport, speed system setup, and prevent accidental relative movement of the cameras postcalibration. Both cameras had been previously calibrated to obtain their intrinsic camera parameters. The board was manufactured from reinforced Medium-Density Fibreboard (MDF) and housed both Wii controllers in slots, cut out such that they were in opposition at an angle of 25° from the midline of the board (see Fig. 1). The horizontal opposition of the WiiMotes was intended to enhance accuracy in the depth direction by ensuring that deviations in the depth direction yielded greater migration of the resolved IR point across

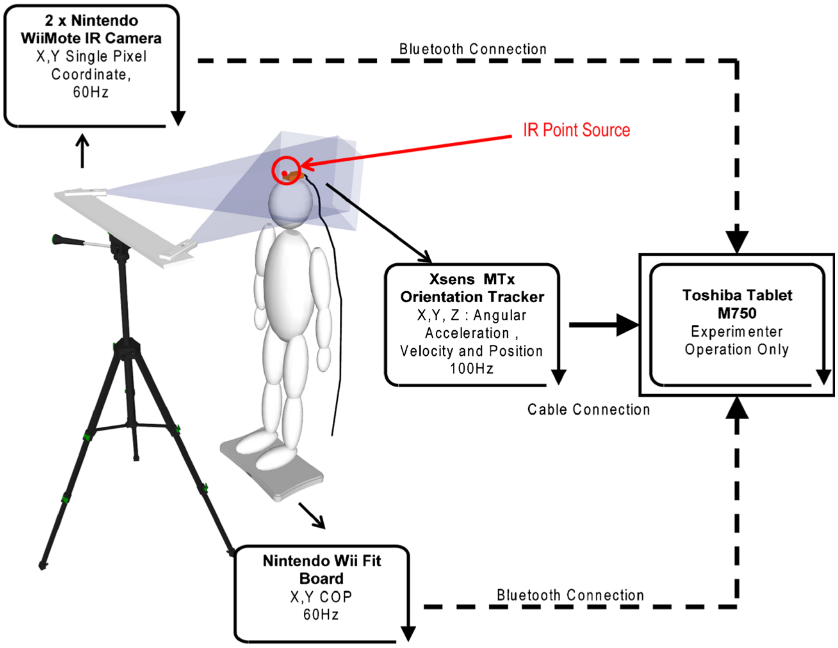

Fig. 1 System schematic. A three-dimensional motion capture system was developed using a pair of Nintendo Wii controllers connected to the host computer via Bluetooth and to a suitable calibration routine that calculated the internal properties of each infrared (IR) camera. A second calibration was then performed that calculated the relative orientation and position of the cameras with respect to each other. The Wii controllers then relayed the *x*- and *y*-coordinates of this source at 60 Hz to the host PC. By triangulating the results from the two controllers, the IR source could be located in three-dimensional space in the same manner as stereoscopic vision. For the purposes of this study, an Xsens device was mounted to the same head strap as the IR-emitting diode. Measures from this device were included so as to provide an initial comparison between the angular and positional measures of postural sway and a validation of the new motion capture system against clinical motion capture equipment

the image planes in both cameras. The camera beams aligned at a distance of 1 m from the front of the board.

To determine the stereo calibration parameters, in a calibration image capture sequence the system acquired snapshots of a four-IR-diode calibration board powered using a 9-V battery. The four IR diodes were placed in a 150-mm square formation. The calibration required the capture (at 0.5 Hz intervals) of between 250 and 350 “images” (2-D coordinates of the IR diodes in the camera image plane) of the stationary calibration board in a range of orientations, distances, and positions across the image. A subroutine was implemented that, due to the passive nature of the markers, was required to ensure the IR source identification and point correspondence between camera images. The subroutine calculated the mean *x* and *y* pixel coordinates of the four IR diodes over the calibration capture sequence. Depending on their average positions in the image (bottom left, bottom right, top left, and top right), each IR source was assigned an identifier that was used to pair the IR diodes between cameras and their known *x*- and *y*-coordinates on the calibration board. Because the routine used a planar calibration board, the known *z*-axis coordinates were set to zero. A stereo calibration optimization routine (Bouget, 1999) was used to determine the relative translation and rotation of the cameras in both camera reference frames. Orientation of the camera reference frames to the world reference was not required and was therefore not performed.

Calibrated accuracy

The motion tracking system’s accuracy was assessed by placing two IR diodes of known pitch (100 mm) on a “wand” that could be readily moved within the operating volume of the WiiMote system. A series of 675 images were captured of the test wand at 5 Hz in a range of orientations and positions within the operating volume. Care was taken to avoid losing the IR diodes from either of the camera images. Using the camera parameters determined from the calibration, the 3-D positions of the IR diodes were calculated retrospectively, and the 3-D distance between the IR diodes on the wand was calculated. For all data points, the deviation from 100 mm was calculated, and the range of errors is represented in Fig. 2. With reference to the wand measurement pitch of 100 mm, the mean error was 0.69 mm (*SD* = 0.33 mm) representing a mean percentage error of 0.69 % (*SD* = 0.33 %). The volume subtended by the wand during the measurement period was calculated at 0.01 m^3 (equivalent to a cube measuring 215 mm along its edges) with an IR diode movement range of 255, 122, and 322 mm in the horizontal, vertical, and depth directions, respectively.

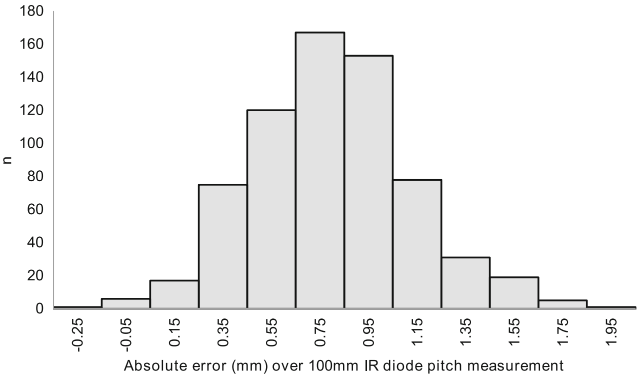

Fig. 2 System accuracy: Histogram of measurement errors of a wand with two infrared (IR) diodes placed 100 mm apart, measured over the full measurement volume and a series of 675 images

Description of the postural measurement system

Previous studies have used the Nintendo Wii Fit board as a substitute for force platforms in the measurement of postural sway (Clark et al., 2010; Young et al., 2011). As with the WiiMote devices, the Wii Balance Board's wireless Bluetooth connection and battery power made it particularly convenient to use outside the laboratory environment, whereas its low cost made it amenable to broad scale deployment. The accuracy of the device in comparison to clinical grade force platforms has been demonstrated in adult populations but optimizing the signal to noise ratio was required if the system was to be used with children (owing to their low mass).

Limiting the effects of quantization noise from Wii balance board

Data collection (Schmid, Conforto, Camomilla, Cappozzo, & D'Alessio, 2002) and biomechanical (Chiari, Rocchi, & Cappello, 2002) parameters have a large influence on spatiotemporal metrics such as COP excursion velocity (Carpenter, Frank, Winter, & Peysar, 2001; Granat, Kirkwood, & Andrews, 1990) and frequency-based measures of postural stability (Ruhe, Fejer, & Walker, 2010). Previous research has highlighted the requirement to standardize data acquisition protocols and filtering methods to facilitate direct between-study comparison of COP metrics (Ruhe et al., 2010).

Sensitivity to these parameters is therefore well established and in a developing population (i.e., children) will likely be exacerbated for two reasons. Firstly, anthropometric and size variability of the participants will be greater across the developmental age range. Secondly, the low mass of the participants in comparison to adult studies might result in the signal comprising a greater ratio of quantization noise to postural sway signal with a corresponding influence on the COP metrics used to quantify postural stability. Thus, it is particularly important to limit the confounding effect of mass-dependent quantization noise on signal acquisition and limit its effect on the spatiotemporal measures of COP behavior, if between-group differences in COP behavior in a developing population are to be interpreted correctly.

Filter design In order to limit the confounding signal-to-noise effects on the COP metrics, a wavelet filter was applied as this could effectively exploit the characteristics of Gaussian white noise (GWN) to determine a noise-related threshold to be applied by the filter for a given participant mass. Using this filtering method, we were able to attenuate the effects of the quantization noise specific to each participant, enhancing the postural signal remaining. Across the mass range of the participants to be tested (6–40 kg), six equally distributed dead-weight recordings of sample length equivalent to the trial length were taken (30 s at 60 Hz = 1,800 samples). The standard deviation of the Gaussian white noise (SDGWN) was calculated on the x and y channels of the COP data for each mass sample. An inverse exponential function was fitted to the mass/SDGWN curve on each axis resulting in R^2 coefficients of .998 and .999 on the x- and y-axes, respectively. The function derived for each axis could then be used to calculate the SDGWN for a participant-specific mass, recorded during testing in quiet stance. The calculated value for the SDGWN for the individual was then used to determine the axis-specific wavelet threshold (T) using Formula 1:

$$T_{x,y} = \sigma_{x,y}\sqrt{2\ \log(n)}, \qquad (1)$$

where n is the number of recorded dead-weight samples and σ is the axis-specific standard deviation of the noise signal. For each axis, the wavelet filter was applied with the relevant axial threshold value. The filter applied was a hard-thresholding, noninvariant, Symmlet 4 mother wavelet filter design with a low frequency cut-off level of 4 Hz (Donoho, Duncan, Huo, & Levi-Tsabari, 1999).

Calculation of standard COP metrics The length of the path subtended by the COP was used as a simple, objective measure of postural stability. When comparing populations with significantly different masses, a problem arises because the Center of Mass (COM) of a larger participant will possess a greater amount of inertia. Small fluctuations to stabilize the COM will therefore have a minimal effect on the COM displacement. When measuring at the COP, this will be observed as a reduction in the path length of the COM displacement but interpretation of the effect of mass is conjecture without a dynamical model linking the kinetics of the COM to the observed COP behavior. For meaningful between-group comparisons of postural stability, a measure robust to the effect of mass on COP displacement is required. The area subtended by the COP over the test time course could provide a measure that represents the containment of the COP within a stability region, typically represented by a best-fit circle or ellipse about the 2D dataset. Postural stability is therefore a function of the areas calculated from these geometries, with a smaller area of best fit being associated with more efficient management of the COM position. Thus, the sensitivity of the metrics to measurement anomalies is reduced by fitting the ellipse or circle to the data falling within the 95 % confidence interval (CI).

Experimental validation methods

A total of 269 children were recruited from two local primary schools. The demographic information is presented in Table 1.

Participants were asked to stand on the Wii Balance board, with their feet a shoulder width apart. Two tests were carried out on each participant: 30 s of quiet standing posture with eyes closed, followed by 30 s quiet standing posture with eyes open. On verbal confirmation that the participant was comfortable, the participant was instructed to close the eyes, and as soon as the eyes were closed, data collection commenced. The experimenter checked that the participant's eyes were closed throughout the test. In the eyes-open condition, the participant was instructed to fix their gaze on a target placed on the WiiMote board at eye level. A short break between conditions allowed us to simply check that the child was comfortable and happy to continue. The conditions were in a fixed order, because we wanted all children to do exactly the same task (to allow for direct comparisons) The WiiMote board tripod was adjusted individually for the height of each individual such that the IR source was at the center of each camera image (1 m from the front of the board).

To quantify the relative sensitivity of the rotational movement versus positional movement in describing head movement during quiet standing, the system synchronously collected data using the IR point source system and a three-degree-of-freedom orientation tracker (MTx, Xsens, Netherlands). The Xsens device was mounted on a stiff, lightweight, adjustable brace strapped to the head of the participant, with the single IR point source being fixed directly to the Xsens device. The Xsens device recorded static (angular position) and dynamic (rate of turn, acceleration) information in the three orthogonal axes of rotation that were measured. We acquired movement data at 100 and 60 Hz for the Xsens and Nintendo devices, respectively, for the duration of the test (Fig. 1). The summed angular rotation about all three axes measured by the Xsens was the output metric for angular motion of the head. The WiiMote position data were postprocessed using the predetermined camera calibration matrices to stereo-triangulate the IR point source position. The output metric from the motion capture system was then calculated as the cumulative path length of the IR diode over the time course of each trial. The raw head rotation (Xsens) and position (WiiMote) data were filtered using a 10-Hz dual-pass Butterworth filter before calculating the output metrics. The Wii balance board data were filtered (using the Wavelet filtering method discussed previously) prior to calculation of the balance metrics.

The output metric from the motion capture system was the cumulative path length of the IR diode over the time course of each trial. The emphasis of the system was simplicity for the user such that the system was usable in-situ by teachers or undergraduate researchers. Marker occlusion is a perennial issue for optical marker systems, and this can lead to significant data loss if the user is unaware of the problem. To minimize this issue whilst maintaining simplicity for the user, a single marker was placed at the highest point on the head avoiding occlusion from narrow camera Field of View (FOV), narrow IR point source FOV, excessive head movements, and the participant's hair/clothing. Following each trial, the system checked connections to the equipment and the quality of the data acquired and highlighted (a) failed connections to any device, (b) no IR point data from either of the cameras, or (c) if more than 10 % of the data over the course of the trial were "missing" from either camera. Tests were repeated if one or more of the following occurred: (1) More than one IR point source was detected by the camera (errant IR sources detected, sunlight in camera FOV); (2) the IR point source was missing in at least one camera for more than 10 % of the test duration; (3) the Xsens or balance board failed to acquire information; or (4) the participant did not follow the instruction to stand as still as possible. Approximately 3 % of all trials were repeated because the above criteria were met.

Table 1 Participant group demographic information

	Nursery/ Reception	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
n	77	46	42	69	44	40	28
Min age (years)	3.2	5.9	6.9	7.8	8.9	9.9	10.9
Max age (years)	5.8	6.8	7.8	8.8	9.8	10.8	11.8
Mean age (years)	5.1	6.4	7.4	8.3	9.3	10.4	11.5
Male	41	20	24	34	22	19	9
Right-handed	67	36	38	64	37	36	26

Results

The data were entered into a mixed-model analysis of variance (ANOVA) with Age Group as a between-participants factor and Viewing Condition as a within-participants factor. We expected to find a reliable effect of viewing condition and a reliable effect of age (under the assumption that movements of the head are related to postural stability). We first inspected the head movement data collected with the Xsens. We did not find a reliable effect of viewing condition [$F(1, 303) = 1.881$, $p = .17$, $\eta^2_p = .006$], but did observe the expected effect of age group [$F(6, 303) = 18.694$, $p < .001$, $\eta^2_p = .27$]. Thus, the Xsens was capturing the changes associated with age, but lacked the sensitivity to detect the differences between eyes open and eyes closed. We then studied the data collected on head movements using our system. A reliable effect of age [$F(6, 311) = 35.518$, $p < .001$, $\eta^2_p = .41$] and viewing condition [$F(1, 303) = 161.044$, $p < .001$, $\eta^2_p = .34$] was found. These results show that our system is capable of producing sensitive data that capture postural effects that are well established in the research literature. It appears that our low-cost system has advantages for measuring head movements over the expensive inertial sensor system (as we hypothesized a priori, on the basis that the inertial sensor needs to detect the small angular changes associated with rotations around the ankles, whereas our system measured positional changes; see Fig. 3).

We next explored the postural (COP) data, and again anticipated reliable effects of viewing condition and age. Reliable effects of age [$F(6, 309) = 11.461$, $p < .001$, $\eta^2_p = .18$] and viewing condition [$F(1, 309) = 171.288$, $p < .001$, $\eta^2_p = .36$] were indeed found for the total COP path length (Fig. 3). Likewise, reliable effects of age [$F(6, 298) = 8.549$, $p < .001$, $\eta^2_p = .15$] and viewing condition [$F(1, 298) = 17.698$, $p < .001$, $\eta^2_p = .06$] were found for the 95 % CI ellipse area. It was possible to explore postural sway across the two orthogonal axes by using the Wii balance board. Human posture is known to be more stable in the medial–lateral plane than in the anterior–posterior plane under a normal standing stance (Winter, 1995). We therefore predicted higher levels of sway in the anterior–posterior plane and an increased effect of viewing condition. Figure 3 shows the path lengths for the COP in the medial–lateral and anterior–posterior planes. A higher level of sway can be seen in the anterior–posterior plane. We found reliable effects of age [$F(6, 307) = 7.947$, $p < .001$, $\eta^2_p = .14$] and viewing condition [$F(1, 307) = 27.035$, $p < .001$, $\eta^2_p = .08$] for the medial–lateral plane, as well as reliable effects of age [$F(6, 306) = 14.904$, $p < .001$, $\eta^2_p = .23$] and viewing condition [$F(1, 306) = 288.055$, $p < .001$, $\eta^2_p = .49$] for the anterior–posterior plane; it can be seen that the effect sizes for detecting differences in age and viewing condition were larger for the anterior–posterior plane. No reliable interactions were observed.

Discussion

We developed a system capable of quantifying postural sway in large numbers of children using widely available and low cost consumer electronics and tested its practicality and sensitivity. The system generated data of sufficient precision to detect the variations in postural stability known to occur over the developmental age range and when the eyes are closed. In addition we compared the head movements measured with our new method to results generated by expensive inertial sensors and found that our low cost positional system provided data that were more appropriate for the application.

A range of measures based on the COP time series or displacement were capable of reliably detecting age and vision effects. Similarly, the motion capture system and the single point translation measure were able to detect reliable differences between participants and viewing conditions. The Xsens device detected reliable reductions in head movement as a function of age but was not able to reliably distinguish a reduction in head movement when visual feedback was present. This confirmed one of our original predictions that rotational measures of head movement would not be sufficiently sensitive to identify subtle differences in quiet stance behaviors (due to the small rotations that occur at the head in quiet stance). Our data therefore suggest that point translation at the head is a more sensitive measure of sway than rotations.

In this study, analysis of the translation of a single point on the head was chosen for two reasons. The first is that a translation of the head yields a translation in the COM with a resultant deviation of the COP. Planar deviations in head displacement (broadly occurring in the transverse plane) can be considered analogous to COP displacement in that both describe displacement of a single point in the transverse plane. Any similarities, or differences between the magnitudes of both measures can then be used to probe differences in postural control strategies. Second, the addition of three markers to generate a reference frame with six degrees of freedom is not suitable for a largely static task in which nominal rotations are anticipated. Moreover, it is easier to monitor the position of a single point of IR light as marker occlusions are easier to manage. Nevertheless, our system would not work well in tasks requiring large head rotations.

COP path length measures are known to be susceptible to quantization noise effects and hence are sensitive to sampling frequency and filtering methods. Our results show the quantization noise effects can be controlled with suitable filtering. We were able to validate our original prediction that the COP measures would be most sensitive in the anterior–posterior direction. The 95 % CI area measure proved to be a robust measure of postural stability, demonstrating that the equipment resolution is sufficient to distinguish the overall movement extents, even when the extent of COP motion is very small.

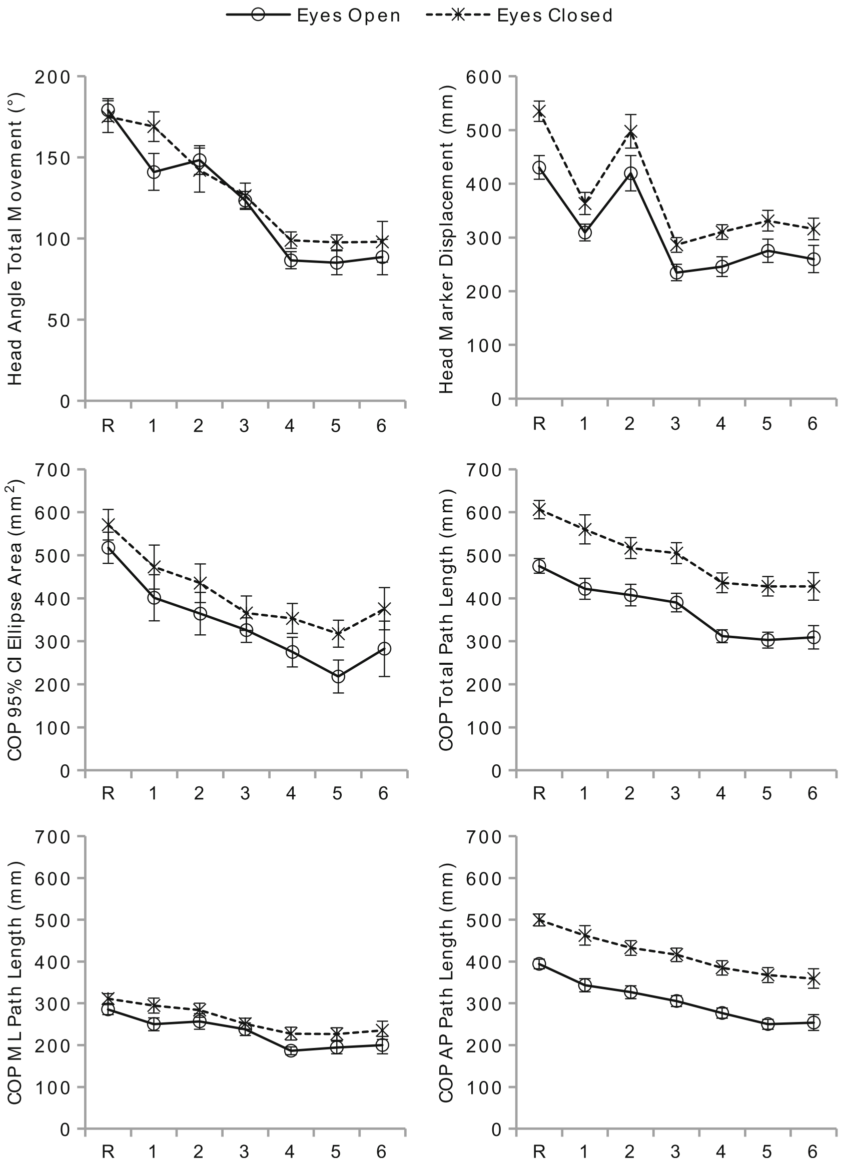

Fig. 3 Postural sway results as a function of year group. The group demographics are detailed in Table 1, and all charts represent data collected over a 30 s trial duration. Upper left panel: Total head movement, defined as the sum of the angular rotations about all three principle axes measured by the Xsens device, and shown as a function of age and vision condition. Upper right panel: Total path length subtended by the head IR diode, shown as a function of age and vision condition. Middle left panel: 95 % confidence interval (CI) area of the Centre of Pressure (COP) data, shown as a function of age and vision condition. Middle right panel: Total path length subtended by the COP as a function of age and vision condition. Bottom left panel: Total deviation of the COP in the Medial–Lateral (ML) direction, shown as a function of age and vision condition. Bottom right panel: Total deviation of the COP in the anterior–posterior (AP) direction, shown as a function of age and vision condition

Crucially, the nature of the equipment used in the study makes it easily transportable, which is perfect for use across different locations (not just in the laboratory). Its compact size does not require a very large testing area to be available, again making it ideal for mobile usage. We have shown that it can easily be taken to test children in settings such as schools and so could be used as a screening tool to detect developmental disorders affecting postural stability, such as developmental coordination disorder (Tsai, Wu, & Huang, 2008). Taking the equipment to children has the benefit of testing them in a familiar, nonintimidating environment, and also means that children do not need to be transported to the laboratory. Because the test is fairly quick and simple to administer, many children can be tested in one session, causing minimal disruption to their day.

Conclusion

We have created a low cost system capable of capturing head and COP data simultaneously. The system was deployed successfully in two schools. The children were happy to wear the head mounted systems and all stood and closed their eyes as instructed. The system was run by undergraduate students following brief training. Thus, the system can be readily used in school settings by nonspecialist personnel (which could easily include the teaching staff within a school). The significant differences found in our reported metrics between age groups suggest that the equipment is sensitive enough to detect subtle changes in postural stability. As well as being a useful tool to study postural development, the measurement system used in the experiment could potentially be used as a diagnostic tool to identify and track children with developmental difficulties (such as Developmental Coordination Disorder).

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