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Validity and reliability of an iPad with a three-dimensional camera for posture imaging☆

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ABSTRACT

Background: It is important to quantify a static posture to evaluate the need for and effectiveness of interventions such as physical management, physiotherapy, spinal orthosis or surgical treatment on the alignment of body segments. Motion analysis systems can be used for this purpose, but they are expensive, require a high degree of technical experience and are not easily accessible. A simpler method is needed to quantify static posture. Research objective: Assess validity and inter and intra rater reliability using an iPad with a 3-D camera to evaluate posture and postural deformity.
Method: A 3-D model of a lying posture, created using an iPad with a 3-D camera, was compared to a Qualisys motion analysis system of the same lying posture, the latter used as the gold standard. Markers on the trunk and the leg were captured by both systems, and results from distance and angle measurements were compared.
Results: All intra-class correlation coefficient values were above 0.98, the highest systematic error was 4.3 mm for length measurements and 0.2° for angle measurements. Significance: A 3-D model of a person, with markers on anatomical landmarks, created with an iPad with a 3-D camera, is a valid and reliable method of quantifying static posture.
Conclusion: An iPad with a 3-D camera is a relatively inexpensive, valid and reliable method to quantify static posture in a clinical environment.

1. Introduction

Posture refers to the position and shape that the body adopts when it is relaxed or during activities. “Good” posture is generally perceived as one that is erect and symmetrically aligned, but it is more accurately defined as a posture that facilitates effective energy conserving function without damaging the body [1]. Posture can have a huge impact on health, as it is potentially damaging to the body system. Any posture, adopted for sustained periods, will put some tissue under stress leading to tissue adaptation, and ultimately contracture and deformity. In individuals with cerebral palsy and lower levels of motor function, postural asymmetries are frequently observed and these asymmetries are associated with secondary complications such as limited range of motion, and scoliosis [2].

The importance of quantifying posture in health and in disease, has been highlighted by several authors [3]. This is required to evaluate the effectiveness of interventions such as physical management, physiotherapy, spinal orthosis or surgical treatment on the alignment of body segments. In order to quantify posture in supine- prone- or side-lying, a reference posture is needed. Usually the anatomical position is considered as neutral (zero-positions) when standing straight with arms by side, thumbs directed forwards, the functional longitudinal axes of the feet parallel and separated by a space equal to the distance between the hips, and the gaze directed forwards and horizontally [4].

In practice, measuring people with deformity and/or displaced body parts in the lying position, such as scoliosis and windswept hips, is not easy to perform with accuracy. This is due to difficulties in identifying the normal anatomical points in the person with significant deformity

☆ This study focuses on the validity and reliability of the use of an iPad with 3-D camera, to evaluate posture in a quantifying way.
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with reference to the corresponding normal zero-position within each of the cardinal planes. Clinical experience has found that angle or distance measurements of deformed body parts cannot be carried out accurately from photographs, due to errors within the camera system, the parallax error and the projection error [5]. Motion analysis system, such as Qualisys, Optotrak, Vicon and Motion Analysis, have been used to assess posture in three dimensions, in a reliable and valid way [3]. However, these systems are not easily accessible for most clinicians since they are expensive, require specialized trained technicians and complex data processing. It is essential for clinicians to have access to valid and reliable clinical measures to properly evaluate effectiveness of interventions used to improve posture [3]. Sato [6] used a two-camera system for evaluating trunk deformity, based on 3-D measurements of body surface landmarks in the frontal plane, expressing rotational and lateral flexion angles between the upper and the lower thorax and between the lower thorax and pelvis. This method is too complicated for use in the clinical environment, as accuracy depends on the camera's resolution, distance to the imaging volume, camera separation and quality of calibration. Total body exposure is not possible with high image resolution and the process involves complex calculation of direct linear transformation parameters [7], which reflects the relationship between the 3-D coordinates of the calibrated volume and the 2D coordinate of the markers within the lens of each camera.

Few years ago, Occipital Inc (USA) made available 3-D scanner (Structure Sensor) that uses a grid of laser to generate a 3-D image of a stationary object within the visual field. This has been marketed as a "3-D camera for iPad". iPad with a 3-D camera is a handheld system that digitally maps the environment (surface topography). The system has the potential to be ideal for the use in clinical environments as the iPad with the 3-D camera does not need any calibration and is designed to be moved around while capturing surface topography. The purpose of the present study was to assess validity, and inter and intra rater reliability, in the use of iPad with a 3-D camera to evaluate posture and postural deformity, for use in the clinical environment.

2. Methods

2.1. Participants

Seven healthy adult volunteers were recruited among colleagues and friends to test validity and reliability of a new method used to evaluate posture and postural deformity. The first participant was used as a pilot to identify landmarks and reference points in two different postures. For the remaining six participants the measuring protocol included four supine postures, starting with supine lying in neutral zero-position; bent hips and knees in the second posture; progressing to an imitated windswept posture in the third and adding scoliosis to the imitated windswept hip deformity in the fourth measurement.

2.2. Instrumentation

The new system consists of a 3-D camera (Structure Sensor, Occipital Inc, USA), integrated with 4th generation version of iPad (Apple, USA), an iPad app (Structure, Occipital Inc, USA) and two computer software Skanect (Occipital Inc, USA) and Cloud Compare (CloudCompare v2.9.1 software, http://www.cloudcompare.org) on a PC computer. The 3-D camera resolution is 320 × 240 pixels (QVGA), sampling at 60 Hz with a precision of 0.5 mm at 400 mm distance from the iPad to the subject. As a gold standard for validation, an 8-camera three-dimensional Qualisys Oqus 300 motion capture system (Qualisys AB, Sweden) and computer software (Qualisys track manager (QTM) Qualisys AB, Sweden) simultaneously recorded markers position, was used for comparison. Qualisys system resolution was 1280 × 1024 pixels sampling at 200 Hz with a precision of ± 1 mm inside the calibrated volume.

2.3. Local frame of reference

The markers used to identify each landmark were Qualisys super spherical reflective markers, 8 mm in diameter, though reflective markers are not feasible to be used with the 3-D camera on the iPad. The 3-D camera sends out a grid of laser onto the environment in front of the iPad while the 3-D camera infrared sensor gathers the reflective light and depth data is generated, from which a digital map of the environment is built. The laser lights up the reflective markers which constantly reflect light to the infrared sensor, causing "shorter" depth to the markers. New layers of surface are laid down on the digital map, while the markers are illuminated. Markers that are not in full view will need longer exposure time using the 3-D camera, as it takes longer time to orient the 3-D camera to capture those markers. However, longer exposure time tends to lead to bigger out of shape marker in the 3-D model.

The 3-D coordinates of the following anatomical landmarks were used to evaluate the orientation of the upper trunk, the lower trunk and the pelvis: right and left: coracoid process, costal margin around the 10th rib and anterior superior iliac spine (ASIS) [1,6]. The x-axis within the local frame was defined as the direction from posterior to anterior when a participant was lying in a supine position, the y-axis was the distal to proximal direction and the z-axis was from medial to lateral (left to right direction).

For the upper trunk local frame, the z-axis was defined as the normalized vector between the left and right coracoid process markers. For the lower trunk local frame, the z-axis was defined as the normalized vector between the left and right lower rib markers. For both the upper trunk and lower trunk local frames, the temporary y-axis was defined as the normalized vector between the mid-shoulder markers and the mid-rib markers. For pelvis local frame, the z-axis was defined as the normalized vector between the left and right ASIS markers; the temporary y-axis was defined as the normalized vector between the mid-rib markers and the mid-pelvis markers. For all three local frames (upper trunk, lower trunk and pelvis), the x-axis was defined by the cross product of the temporary y-axis and the z-axis, and the final y-axis was then defined by the cross product of the x-axis and the z-axis.

Trunk symmetry [1] measures for quantifying scoliosis, is a standardized measurement in the Swedish national surveillance program and quality registry for cerebral palsy (CPUP) [8], by measuring distance, vertically and diagonally, between the coracoid processes and the ASIS.

The 3-D coordinates of following anatomical landmarks were used for evaluating the orientation of left thigh and shank: the greater trochanter, the lateral and medial epicondyle of the femur, the lateral and medial malleolus. For thigh local frame, the z-axis was defined as the normalized vector between the lateral and medial epicondyle markers. The temporary y-axis was defined as the normalized vector between the greater trochanter marker and the lateral epicondyle marker, and the x-axis was defined by the cross product of the temporary y-axis and the z-axis. The final y-axis was then defined by the cross product between the x-axis and the z-axis. For shank local frame, the z-axis was defined as the normalized vector between the lateral and medial malleolus markers. The y-axis was defined as the normalized vector between the lateral epicondyle marker and the lateral malleolus marker. The x-axis was defined by the cross product of the y-axis and the z-axis.

2.4. Protocol

Each participant lay supine on a plinth. The measurements were taken at the movement analysis laboratory by the same experienced physiotherapist and biomedical engineer. Although the recording time was different, five seconds for the Qualisys and more than a minute for the iPad, both systems started recording participants simultaneously. The output from the two systems have different formats, the Qualisys system output are markers location in 3-D space while the iPad systems

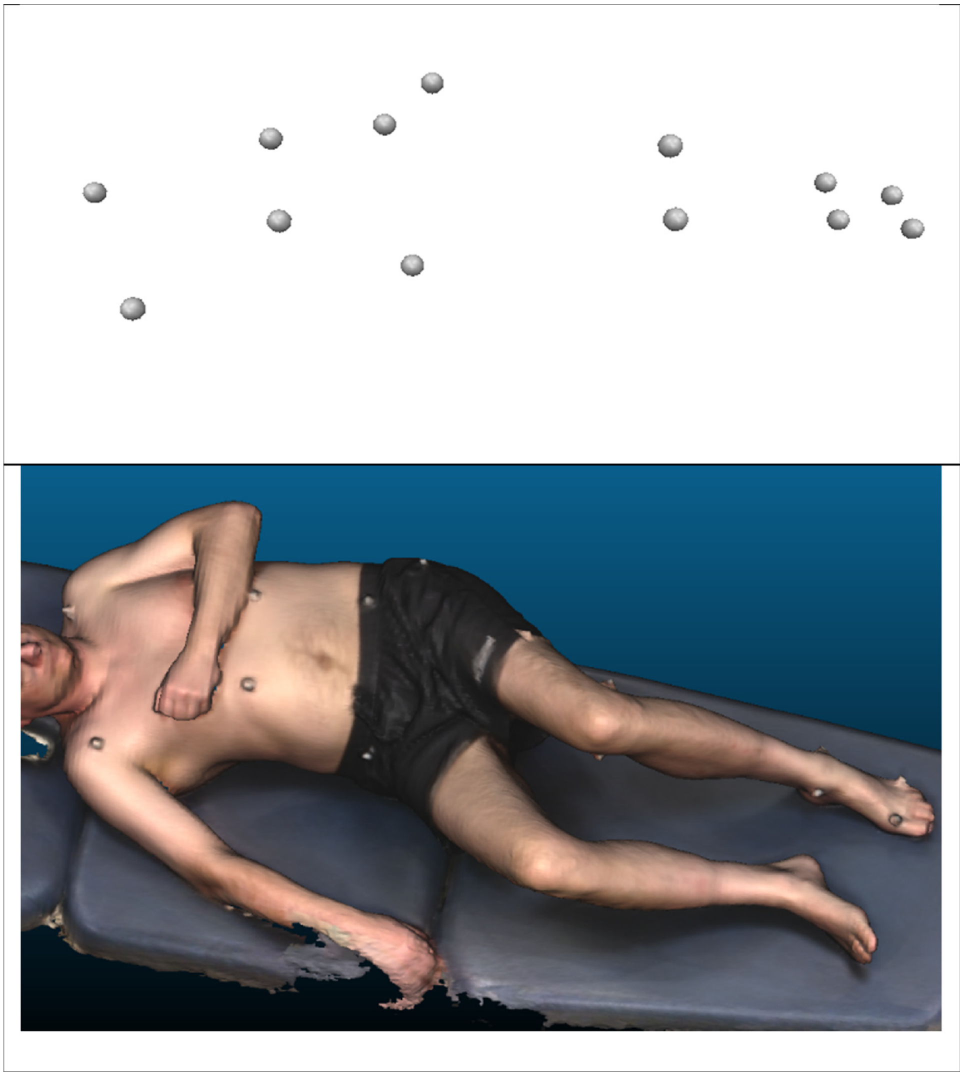

Fig. 1. a) Output from the Qualisys system; b) Output from the iPad system.

output is a 3-D model of the individual posture (Fig. 1).

During the iPad 3-D scanning, the iPad with the 3-D camera, was hand-held and carried two times around the plinth as a surface topography of the participant lying in supine appeared on the iPad screen. The distance from the iPad to the participant varied within every session, between 400 mm to 1000 mm. The recording time was about 1 min. The surface topography was simultaneously streamed into the Skanect software on a PC computer, via Wi-Fi uplink, for storage. During post processing in the Skanect software was the surface topography reconstructed and fused into a 3-D model and exported on a PLY format. The PLY file was opened in CloudCompare v2.9.1 software, (http://www.cloudcompare.org) where the markers were identified and its position in 3-D space manually digitised on the surface of every marker and exported as an ASCII file.

The Qualisys Oqus 300 captured the markers position in 3-D space and the QTM digitised the markers position in the centre of each of the marker. Recording time 5 s. During post processing in QTM markers in every posture (session) were manually identified and each session was exported on a C3D format (https://www.c3d.org/). Both the manual identification of markers in the QTM and the manually digitisation of markers in the Cloud Compare software, are the most critical factors to accurately determine the markers location.

2.5. Data analysis

Matlab (Version R2017b, Mathworks Inc, Natick, USA) script calculated trunk and knee angles (degrees) and trunk symmetry lengths (mm) from data in the C3D and ASCII files. One frame, frame 100 in the C3D file, was used in the calculation. Three-dimensional coordinate systems were created for each segment based on the marker position. Unit direction vectors of each segment were placed into a matrix representing a three-dimensional rotation matrix for each segment. The rotation matrix was a 3 × 3 matrix on the form

$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}$$

The rotation of each segment was calculated using the formula

$$\varphi = \tan^{-1}\left(\frac{R_{21}}{R_{11}}\right)$$

$$\theta = \tan^{-1}\left(\frac{-R_{31}}{\sqrt{R_{11}^2 + R_{21}^2}}\right)$$

$$\psi = \tan^{-1}\left(\frac{R_{32}}{R_{33}}\right)$$

where φ represented flexion/extension, θ represented ab/adduction and ψ represented internal/external rotation.

The joint angles were calculated as the relative three-dimensional rotation between interconnecting segments using the set of equations above. The joint angles were angles in degrees between upper trunk and lower trunk, angles between lower trunk and pelvis and angles between thigh and shank. The distance extracted from the analysis was the length in millimetres between the right coracoid process and right ASIS, right coracoid process and left ASIS, left coracoid process and left ASIS, left coracoid process and right ASIS. The output from Matlab was copied into Excel (Excel, Microsoft, USA) where the data was organized for statistical analysis.

A systematic digitizing bias at each marker (8 mm in diameter) can theoretically be between minus 4 mm to plus 4 mm, and thus ± 8 mm for calculation of a length between two markers. The Qualisys system digitizes in the centre of the marker while the iPad system digitises on the marker surface. Criterion related validity was established using the Qualisys system as gold standard, evaluated as concurrent validity since they were measured at the same time. The evaluation of intra-rater reliability was based on data from three repeated measurements when digitising the markers of the same 3-D model in the CloudCompare software by the same physiotherapist. The analysis of inter-rater reliability was based on data from three experienced physiotherapists, who digitised the markers in the CloudCompare software, for each measurement. A limits of agreement plot (Excel, Microsoft, USA) was used to evaluate bias between the mean differences of the measurements and to estimate the agreement interval, within which 95% of the differences of the mean lie. Mixed model ANOVA SAS 9.4 (SAS Institute Inc, USA) was used to evaluate the effects of the mean differences of the measurements, i.e. the systematic error and its significance level, and to calculate the intraclass correlation coefficient (ICC(2,k) and ICC(3,k) [9] together with the standard error of measurement (SEM).

3. Results

The seven volunteers, aged 20–57 years (4 females, 3 males), generated a total of 26 measurements of supine postures. Four of these measurements had missing markers in the Qualisys system data and were not included in the analysis, leaving 22 complete measurements. Table 1 shows the parameters of the intra-rater and inter-rater reliabilities (ICC, SEM and systemic error) for four selected measurements using the iPad system, as well as the validity parameters (iPad - Qualisys comparison). These four measurements are the length measurements (Fig. 2), Upper-Lower trunk angles (Fig. 3), Lower-Pelvis angles (Fig. 4) and knee angles (Fig. 5).

All ICCs were above 0.98. SEM for the length measurements was lowest for intra-rater reliability, 2.3 mm, and slightly higher for the inter-rater and validity comparisons. Systematic error was 4.3 mm for the validity comparison but less than half of that for the reliability comparisons. For the three angle measurements, SEM were less than 1° for Upper-Lower and Lower-Pelvis angles and 1.5° or less for knee angles. Systematic error was 0.2° or less and non-significant in all analyses.

4. Discussion

The aim of this study was to assess intra- and inter-rater reliability and validity in the use of an iPad with a 3-D camera to evaluate posture and postural deformity. Our results show that, in quantifying posture, there is a high correlation between the outcome from iPad with a 3-D camera and the Qualisys system. The result thus clearly indicates that the use of iPad with 3-D camera can be used in clinical environments, with sufficient accuracy for quantified evaluation of posture and postural deformity. There is no need for calibration of the volume when using 3-D camera and iPad and total body 3-D models are readily analysed. Furthermore, 3-D models of an individual can be saved for reference later. The intraclass correlation coefficient (ICC) (Table 1-4) indicates excellent assessment of accuracy and consistency, both between the Qualisys system and the iPad system (validity), and the intra- and inter-rater reliability. ICC values from 0.98 indicate that there is an excellent reproducibility by the iPad system.

Cerebral palsy is a well-recognised neurodevelopmental condition that manifests in early childhood and persists throughout life [10]. It is the most common physical disability in childhood, with a prevalence of 2.0–2.4/1000 live births in Europe [11,12]. Although the need for quantification is common to a wide range of diseases and types of disability, it is especially valid in cerebral palsy due to the frequent occurrence of postural deformities. Even though the main objective of this study is to compare the accuracy and correlations between two methods quantifying posture in general, the test positions were particularly chosen with some of the most common postural problems of cerebral palsy in mind.

The difference in right and left vertical length, in the trunk symmetry measurement, indicates the degree of asymmetry in lateral flexion, whereas the difference in the right and left diagonal length indicates the degree of asymmetry in rotation of the trunk. Using surface topography reconstructed by iPad, the shortest distance between landmarks is automatically selected, filtering out error effect from the body itself, that will affect the measurement when using a standard measuring tape. The systemic error is less than 2 mm when assessing the reliability and is smaller than SEM (Fig. 2) indicating good precision of the system. In the validity measurement, the mean difference is 4.3 mm indicating that the output from the two systems, iPad with 3-D camera and Qualisys, are not too different. The reason for this difference arises from the systematic digitizing bias between the two systems, as they localize differently the reference point on the marker (see the method section for further details).

The conventional method to evaluate posture is to measure the joint angles of the human body [4] with a goniometer. The results from these conventional methods of measuring joint angles and calculating 3-D joint angles are usually not the same, due to different local frames of reference and the effect from the order of rotation in 3-D angle calculation [13]. In all angular measurements, the difference of mean

Table 1
Agreement between raters and measurements.

	ICC(2,1)	ICC(3,1)	SEM	Systematic error	p
Trunk symmetry measurements					
Intra-Reliability	0.997	0.996	2.34	0.8 mm[a]	< .001
Inter-Reliability	0.994	0.997	2.92	1.9 mm[b]	< .001
Validity	0.995	0.991	2.80	4.3 mm[c]	< .001
Upper-Lower trunk angle					
Intra-Reliability	0.992	0.992	0.45	0.1°	0.779
Inter-Reliability	0.990	0.991	0.51	−0.1°	0.808
Validity	0.982	0.982	0.69	−0.1°	0.475
Lower-Pelvis trunk angle					
Intra-Reliability	0.999	0.999	0.45	−0.1°	0.225
Inter-Reliability	0.998	0.998	0.62	0.1°	0.469
Validity	0.997	0.997	0.72	0.2°	0.131
Thigh-Shank (knee) angle					
Intra-Reliability	0.997	0.997	1.29	−0.1°	0.144
Inter-Reliability	0.997	0.997	1.25	−0.2°	0.246
Validity	0.995	0.995	1.50	−0.1°	0.586

All trunk symmetry measurements are pooled together, all Thorax upper-lower angles are pooled together, all Thorax lower-pelvis angles are pooled together and all thigh-shank angles are pooled together.

[a] The systematic error is the average difference between the first and the second measurement and the first and the third measurement of the 3-D models.

[b] The systematic error is the average difference between Rater 1 and Rater 2, Rater 1 and Rater 3 and Rater 1 and Rater 4, measurement of the 3-D models.

[c] The systematic error is the difference between Qualisys system measurement and the IPad 3-D model measurement.

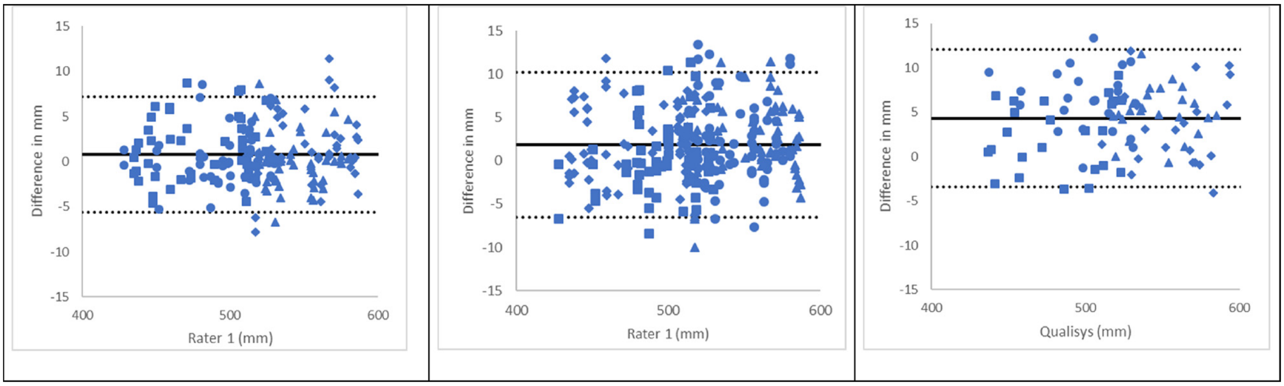

Fig. 2. Distances between: right coracoid process and right ASIS ■, right coracoid process and left ASIS▲, left coracoid process and left ASIS •, left coracoid process and right ASIS ◆. a) Intra-rater reliability (difference in length measurement between the first and the second measurement and the first and the third measurement of the IPads 3-D models, pooled in the graph); b) Inter-Rater reliability (difference in length measurement between Rater 1 and Rater 2, Rater 1 and Rater 3 and Rater 1 and Rater 4, of the IPads 3-D models, pooled in the graph); c) Validity (the difference of length measuremetns between the IPads 3-D model measurement and the Qualisys system measurement). Solid line shows the mean difference for the pooled data. Dashed lines show the 95% upper and lower limits of agreement representing two standard deviations above and below the mean difference.

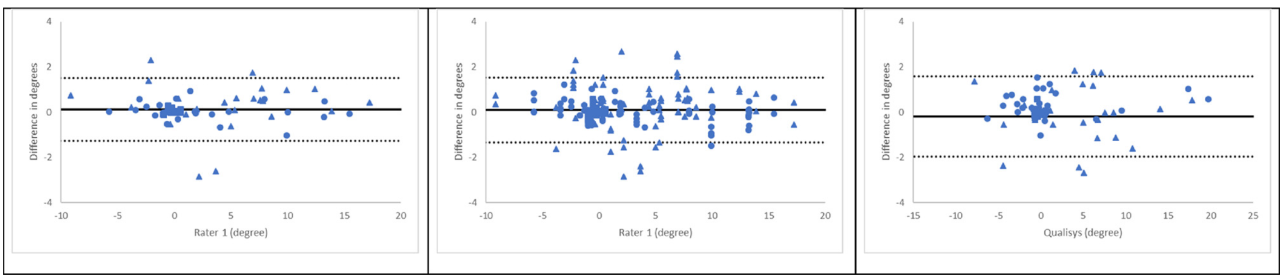

Fig. 3. Thorax Upper-Lower angles. Pooled angles: Flexion / Extension ■, Lateral flexion▲, Rotation •. a) See Fig. 2a for further explanation; b) See Fig. 2b for further explanation; c) Validity. The difference of calculated Upper-Lower angles between the IPads 3-D model measurement and the Qualisys system measurement. See Fig. 2c for further explanation.

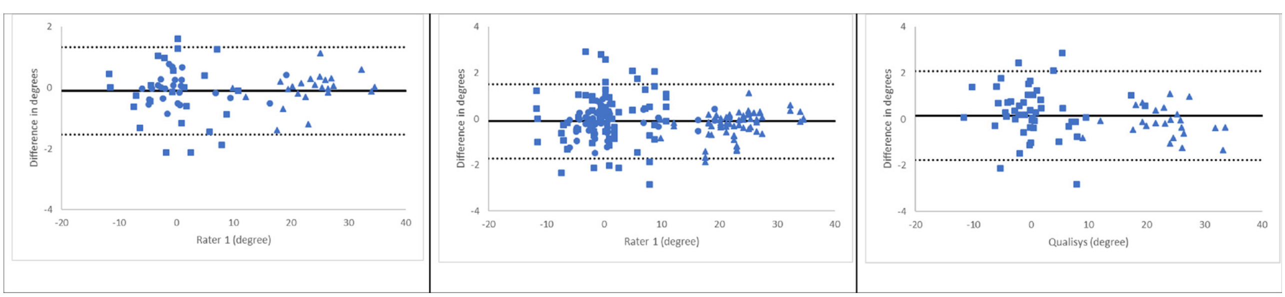

Fig. 4. Thorax Upper-Lower angles. Pooled angles: Flexion / Extension ■, Lateral flexion ▲, Rotation •. a) See Fig. 2a for further explanation; b) See Fig. 2b for further explanation; c) See Fig. 3c for further explanation.

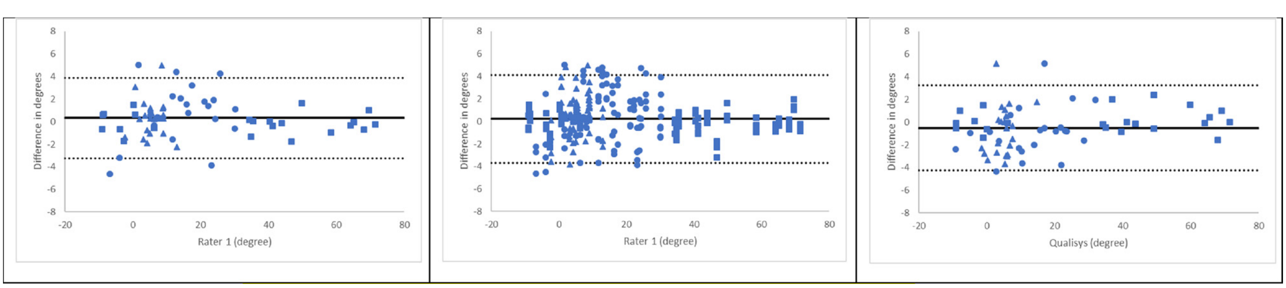

Fig. 5. Knee angles. Pooled angles: Flexion / Extension ■, Lateral flexion ▲, Rotation •. a). See Fig. 2a for further explanation; b) See Fig. 2b for further explanation; c) See Fig. 3c for further explanation.

between the gold standard (Qualisys) and the new iPad system, was negligent (Fig. 3–5). Each local reference segment, constructed from three markers on each segment, filters out the effect from the discrepancy of individual marker location, during angle calculation. In both trunk angle measurements, the SEM of the difference was lowest during intra-rater reliability test and highest during the validity test.

The range of the limits of agreement, in the trunk measurements, were around four degrees, which is well within any clinical environment error [14]. The SEM of the difference in the knee angle measurement results are higher than in the trunk angle measurement results, with the range of limits agreement being around eight degrees. The high digitizing error found at the knees and ankles, during imposed windswept posture, is due to big out of shape markers next to the plinth in the 3-D model. As the marker gets bigger and more out of shape, the digitizing bias increases as the distance from the markers surface to its centre gets longer.

Though the use of reflective marker was needed in this study for comparison with the gold standard measurement (Qualisys), it is not necessary in the clinical environment when the iPad system is used. In the clinical environment, any type of marker that is not reflective will hold its form during the surface topography. Markers that are not out of shape will lessen the digitizing error and smaller digitizing error would lead to similar reliability (SEM) in the knee angles as is in the trunk angles. This study suggests that the ideal marker for an iPad with 3-D camera postural evaluation would be a half spherical with a checkerboard pattern, in order to pinpoint accurate digitization.

A limitation of this study lies in the use of healthy subjects to evaluate the validity and reliability of the method for quantifying posture proposed for use with motor impairments such as CP. However, a 3-D model of an individual (Fig. 1), for evaluating posture and postural deformity, depends on visibility of anatomical landmarks, not on being able or disabled. There is no reason to expect that the validity and reliability of a 3-D model, differ between individuals with or without motor impairments. However, subjects unable to stay still while constructing surface topography are not candidates for this type of static posture evaluation.

5. Conclusion

The use of an iPad with a 3-D camera to evaluate posture and postural deformity shows a high correlation and good validity with the output from the Qualisys system, along with high intra- and inter-rater reliability. The results clearly indicate that the use of iPad with 3-D camera can be used in the clinical environment, with good accuracy, for evaluating posture and postural deformity.

Conflict of interest

The authors report no conflict of interest. The authors alone are responsible for the content and writing of the paper and the manuscript is not under consideration for publication elsewhere.

Author contribution

Atli Ágústsson: Designed the study, collected the data and analyzed the result, drafted, improved and revised the manuscript and approved the final draft.

Magnús Kjartan Gíslason: Designed the study, improved and revised the manuscript, and approved the final draft.

Páll Ingvarsson: Improved and revised the manuscript and approved the final draft.

Elisabet Rodby-Bousquet: Designed the study, improved and revised the manuscript, and approved the final draft.

Þórarinn Sveinsson: Designed the study, analyzed the result, improved and revised the manuscript, and approved the final draft.

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