Obtaining patient torso geometry for the design of scoliosis braces. A study of the accuracy and repeatability of handheld 3D scanners.

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Obtaining patient torso geometry for the design of scoliosis braces. A study of the accuracy and repeatability of handheld 3D scanners.

Abstract

Purpose Obtaining patient geometry is crucial in scoliosis brace design for Adolescent Idiopathic Scoliosis (AIS) patients. Advances in 3D scanning technologies provide the opportunity to obtain patient geometries quickly with fewer resources during the design process compared to the plaster-cast method. This study assesses the accuracy and repeatability of such technologies for this application.

Methods The accuracy and repeatability of three different handheld scanners and phone-photogrammetry was assessed using different mesh generation software. Twenty-four scans of a single subject´s torso were analyzed in terms of accuracy and repeatability based on anatomical landmark distances (ALDs) and surface deviation maps.

Results Mark II and Structure ST01 scanners showed maximum mean surface deviations of 1.74±3.63mm and 1.64±3.06mm, respectively. Deviations were lower for the Peel 1 scanner (maximum of -0.35±2.8mm) but higher using phone-photogrammetry (maximum of -5.1±4.8mm). Mean absolute errors of ALD measurements from torso meshes obtained with the Peel 1, Mark II, and ST01 scanners were all within 9.3mm (3.6%) while phone-photogrammetry errors were as high as 18mm (7%).

Conclusion Low-cost Mark II and ST01 scanners are recommended for obtaining torso geometries due to their accuracy and repeatability. Subject’s breathing/movement affects the resultant geometry around the abdominal and anterolateral regions.

Keywords; 3D Scanner; Scan accuracy; Torso geometry; Scoliosis brace; Adolescent idiopathic scoliosis

Introduction

Adolescent idiopathic scoliosis (AIS) affects approximately 2.5% of the population [1,2]. Conservative treatment is initially recommended with surgery being considered for patients presenting severe deformities [3,4]. Conservative treatments aim to either correct the deformity, or to stop curvature progression thus avoiding surgical intervention, bringing both patient and economic benefits [5,6]. Conservative treatments include bracing, electro-stimulation, and physiotherapy [5,7]. A randomised controlled trial conducted by Weinstein et al. [8] demonstrated the effectiveness of wearing a brace to reduce AIS progression, confirming this as the treatment of choice for the conservative management of AIS [9]. Whilst this supports the use of bracing, less is known about the optimal design and geometry for these braces.

Most scoliosis braces are customized for each patient and therefore the torso geometry needs to be obtained during the design process. Most commonly a plaster-cast method is used to replicate the patient's geometry, creating a positive mould that is manually rectified into a geometry that the orthotist believes will prevent deformity progression. The brace material is then moulded and trimmed accordingly to create a custom brace. The design process is heavily reliant upon the skills and expertise of the orthotist, requiring significant time and resources.

Previous studies have used computer aided design (CAD) approaches as an alternative to the plaster-cast method showing benefits in terms of in-brace correction and treatment success in AIS patients [10,11]. This method involves scanning the patient's body surface, a technique that has been assessed for use in clinical applications on hand orthoses [12], the assessment of the human foot [13], and prosthetic socket design [14]. Nevertheless, these studies have focused on other body parts and therefore their accuracy results are not transferable to the torso geometry. Surface topography and 3D scanners have been used in patients for the assessment of torso asymmetry

[15,16] and for the analysis of scoliosis progression as alternative non-invasive methods to X-ray examinations [17]. The reliability of torso measurements from 3D scans using surface topography has been previously studied [18], however, the employed 3D scanning and reconstruction technologies were used to assess the torso shape, and the accuracy of the systems was not reported. The accuracy of different 3D surface scanners for the assessment of spinal deformity was studied by Grant. et al. [19] but the analysis involved scanning an object that replicated patient anatomy and spinal curvature (a torso plaster casts) rather than direct scanning of patients. Thus, a greater understanding is needed regarding the accuracy and repeatability of 3D scanners to scan a patient´s torso and locate anatomical landmarks, fundamental for the design of scoliosis braces. This study aims to fill these gaps by obtaining the torso geometry of a living patient to understand the effects of movement and breathing on obtaining torso geometries and compare the accuracy and repeatability of different 3D scanning technologies. The objective is to reduce the time and resources (rectification tools, Plaster of Paris bands, and casting powder) required to design scoliosis braces and investigate digital alternatives to the plaster-cast method, building on previous work in this area where 3D scanners were used to characterise the mould rectification process [20].

Materials and methods

Scanners

Three different scanners and a smart-phone were used in this study: Peel 1 (Creaform Inc., CA), Structure Sensor Mark II (Occipital Inc., USA), Structure Sensor ST01 (Occipital Inc., USA), and a Samsung SM-G960F (Samsung Electronics Co. Ltd., SK). These were chosen because they are portable, and represent a wide range of accuracy, resolution, price, and scanning technologies (Table 1), following the same criteria used in a previous study that investigated the accuracy of 3D handheld scanners for spinal deformity assessment [19]. Operation of the scanners and torso mesh generation was performed using a Microsoft Surface 4 Pro for the Peel 1 and an iPad mini 4th Gen for the Mark II and ST01. The resolution scan parameter for the Peel 1 was set to 2mm. Photographs from the phone were used to generate the mesh using the photogrammetry software Meshroom (AliceVision).

Insert Table 1

Preparation for scanning

A single subject, who had been assessed by an experienced clinician, was deemed to have no spinal deformities, injuries or abnormalities located in the torso, was recruited for this study. The subject wore a white compression shirt to better reflect light to the scanners, to minimize the influence of clothing, and to follow the clinical practice used during the casting method. Lighting was even from all angles, reducing the influence of light which has previously been shown to affect Structured Light 3D scanners [21]. Ethical approval was obtained from the Research Ethics Committee (approval number: 20IC5750).

Calibration and accuracy assessment

Markers were placed on anatomical landmarks of the torso and pelvis that were deemed fundamental for the design of scoliosis braces for AIS patients. For this the International Society of Biomechanics (ISB) guidelines [22,23], were followed such that markers were placed at the xiphoid process of the sternum (STRN), right/left anterior superior iliac spine (R-ASIS/L-ASIS), right/left angulus inferior scapulae (R-AI/L-AI) and right/left posterior superior iliac spine (R-

PSIS/L-PSIS) (Figure 1(d) and 1(h)). Markers were sprayed with white paint to avoid light absorption that causes voids on dark objects.

Scanning process

The torso geometry was obtained three times with each scanner/software combination resulting in a total of twenty-four scans for the selected standing posture (Figure 1(d) and 1(h)). During scanning the subject was asked to stand with arms flexed anteriorly and hands in front of the face away from the torso and keep the same standing posture during each scan, following a similar posture to the anatomical posture adopted in other clinical studies [24,25]. The investigator moved around the subject with the scanner held in a vertical position, using floor markers as a reference to maintain a constant distance between the scanner and the subject's body, sweeping the torso area until the scan was completed. To ensure that the entire torso geometry was captured with minimal error, the subject was asked to breathe as they normally would and stand as still as possible. After each scan, the subject was given time to rest in a normal standing position so they could recover before the next scan. The scanning process was performed randomly by three different investigators, to avoid user experience bias. This involved an investigator being assigned to use one software/scanner combination, which they then used a total of three times for the purpose of assessing repeatability.

Software and mesh generation

Different software tools were used for the different scanners. For the Peel 1, Peel 3D software interface (Creaform Inc., Quebec, Canada) was used to scan and generate the mesh. The Peel 1 scans resulted in meshes with isolated voids (Figure 1(c)) that required post-processing to cover them and remove noise to generate a uniform mesh (Figure 1(e)). For the Structure Sensors (ST01 and Mark II) three different software applications were used to compare their influence on accuracy and repeatability: App (D) - DigiScan (LifeEnablec Inc., USA), App (O) - Occipital/Scanner (Occipital Inc., USA), and App (T) - 3DSizeMe (TechMed 3D Inc., CA). Scanning and mesh processing times were recorded for each scan. Photographs taken with the phone were processed using the open-source photogrammetry software Meshroom (AliceVision), generating a point cloud and cloud to mesh transformation. The resulting meshes were post-processed to smooth the torso surface with Blender open-source software.

Data analysis: Accuracy and repeatability

Two types of analysis were performed: (1) Comparison of anatomical landmark distances (ALDs) between manual measurements and measurements from the 3D scans, and (2) comparison of 3D surface deviations between the torso meshes following the visualization standard used in prosthetics [26].

Anatomical landmark distance comparison

Prior to scanning, anatomical landmark distances (ALDs) were manually measured three times using a calliper on both the anterior (R-ASIS/L-ASIS, STRN/R-ASIS and STRN/L-ASIS) (Figure 1(d)) and posterior (L-PSIS/R-PSIS, L-AI/R-AI, L-AI/R-PSIS and R-AI/L-PSIS) sides (Figure 1(h)). Each distance was also measured three times from 3D torso meshes generated for each combination of scanner/software using Blender (red lines - Figure 1). For the Peel scans, since mesh voids were present in marker locations, 3D marker parts were overlapped in Blender matching the voids allowing ALDs to be measured (Figure 1(c)). Mean values were obtained from each of the three repeats made with each combination of scanner and software and compared to the mean of the manually measured anatomical distances to quantify differences between the manual measurements and the CAD torso meshes (Figure 3). Mean Absolute Errors (MAE) and Standard Deviation (SD) values were calculated for the different scanners for each

ALD with respect to the mean of the manual measurement and classified for each mesh generation software. The errors were expressed in mm and as a percentage to indicate the size of error versus the size of measurement (Table 2).

Insert Figure 1

3D Surface deviation comparison

Determining the accuracy of the different scanners required a reference scan that was regarded as the most representative geometry. For this purpose, the Peel 1 was selected due to its high accuracy and resolution stated by the manufacturer (Table 1), and low ALD errors. The absence of voids at marker locations, and low ALD errors were used to select one of the three Peel 1 meshes (scan 24), as the reference for this analysis. 3D surface deviations between the reference scan and all other meshes were computed using cloud to mesh (C2M) distances (CloudCompare open software).

Results

Anatomical landmark distances

Figure 2 shows the ALD results for each scanner using independent polygonal graphs compared to the mean of the manually measured anatomical distances (green inner polygon). Results using all three software apps are shown for the Mark II and ST01 scanners.

Insert Figure 2

Figure 3 represents the mean ALD, and the corresponding maximum and minimum deviations compared to the manual measurements. The numerical values are shown in Table 2.

Insert Figure 3

Insert Table 2

3D Surface deviation comparison

3D surface deviation maps show the distribution of deviations from the reference scan (Peel 1 - Scan 24) and each scanner and software used over the subject's torso surface (Figure 4). Maximum negative deviations were located on the anterolateral sides and the abdominal area. Histograms and normal distributions (ND) classified by mesh generation software/app are shown in Figure 5. Mean errors, standard deviations, and 95% confidence intervals calculated for each scan are listed for each mesh generation software in Table 3.

Insert Figure 4

Insert Table 3

Insert Figure 5

Discussion

In the present study, we scanned a subject´s torso using structured light (SL), active stereo (AS), infrared structured light (ISL) and phone-photogrammetry technologies comparing the accuracy and repeatability of both the scanners and the mesh generation software. This is the first study to look at the accuracy and repeatability of using handheld scanners on the subject's torso rather than a stationary object, where breathing and movement can influence the acquired geometry. Other studies have scanned torso casts to produce 3D meshes for the clinical application of spinal deformity assessment [15–17], but none have focused on its application to scoliosis brace design, and none have investigated their use for measuring anatomical landmark distances, which is particularly important for orthotists during the rectification process.

Anatomical landmark distances (ALDs) measured from torso meshes generated with the Peel 1 scanner had an average mean absolute error (MAE) of 4.7mm (1.8%) which was the lowest of all the scanners when compared to the manual measurements (combining errors from all seven ALD measurements - Table 2). The Mark II and ST01 scanners had average MAE of all ALDs from 5.6mm (2.2%) to 9mm (3.5%) and from 8mm (3.1%) to 9.3mm (3.6%), respectively (range for the three software), when compared to the phone-photogrammetry, which on average had MAE of 18.0mm (7%) (Table 2). These results demonstrate that the Peel 1 scanner provided the most accurate results when measuring ALDs. However, the error was not that different when compared to the Mark II and ST01 scanners (within 1.8%). Moreover, these scanners shorten substantially the scan and mesh generation times. ALD measurements made from torso meshes generated using phone-photogrammetry resulted in maximum errors of 30.3mm (R-AI/L-PSIS – Table 2).

The normal distributions of the point cloud datasets for the 3D surface maps (Figure 5) and the difference between the maximum and minimum mean surface deviations were used to analyse the repeatability of the scanners. ALD data was not used in the repeatability analysis due to the low statistical power of having just seven measures for each scan. A close match was seen in mean surface deviations between repeat scans when using all scanners and software/app combinations (mean errors within 1.80mm – Figure 5(a-h) and Table 3) apart from with phone-photogrammetry (mean errors within 2.15mm). Surface deviations were small between the reference scan (Peel 1 – scan 24) and all other scanner and software/app combinations (maximum mean error of 1.74mm (Scan 5 - Mark II/Digiscan App – Table 3 and Figure 5(i)) apart from phone-photogrammetry, which had mean errors up to 5.06mm. Looking at Figure 4, it could be seen that subject breathing/movement affected the accuracy of the meshes. Larger deviations were located particularly in the abdominal and anterolateral side regions of the torso where deviations were consistently between 7 and 12mm, regardless of the scanner or mesh generating software that was used. Deviations associated to breathing and movement are likely to be ever present when scanning a patient in a standing posture, however procedural improvements may limit these effects by, for instance, supporting the torso and pelvis at certain anatomical points. Reproduction of this study on a large AIS patient group is also required to determine whether spinal deformities show other areas with larger deviations or whether results differ between patients with different spinal curvatures, severities of deformity, breathing patterns, body masses, and soft tissue compositions. Brace designs must accommodate the 7-12mm deviations that were seen in the abdominal and anterolateral side regions of the torso such that patients are able to breathe normally while wearing them. It therefore may be appropriate to use these values as a guide as to what is acceptable in terms of gross inaccuracy across the full orthosis design and fabrication process. Using these limits, all the scanners assessed in this study except the phone-photogrammetry would be acceptable for the purpose of obtaining torso geometries for designing AIS orthoses.

It was expected that since the Peel 1 scanner had a longer scan time (119s) compared to the Mark II and ST01 scanners (less than 47s) that artifacts due to the patient moving or breathing would be more pronounced in the Peel 1 data. However, the scanners performed comparably in terms of surface deviations (Figure 4) and the Peel 1 had a lower mean error than the other scanners (Figure 5). Despite this, a shorter scan time is still likely to be advantageous, particularly for AIS patients with more severe deformities where holding a posture for a long period of time may be challenging. The software that was used for the Mark II and ST01 scanners had a slight effect on the scan time (<22s) with Digiscan being the fastest (mean=26s for the Mark II and 23s for the ST01 - Table 2). Additionally, the Mark II and ST01 scanner produced meshes in less than 10 seconds compared to 38 and 105 minutes (including post-processing time) for the Peel 1 scanner and phone-photogrammetry technique, respectively which is advantageous in a clinical setting.

Although this study used different hardware, the scanner resolutions were similar and the technology (White LED SL and ISL scanners) was the same as a previous study where torso casts were scanned [19]. They reported mean surface deviations of 0.17±0.17mm for an Artec Eva (White LED SL) scanner can be compared to the high-resolution Peel 1 scanner (White LED SL) used in this study which showed maximum mean surface deviations of -0.35±2.82mm (Table 3). They also used a Microsoft Kinect (ISL) scanner, which had mean surface deviations of 1.58±1.50mm, which compares well with the ST01 (ISL) scanner used in this study (surface deviations between 0.13±2.80mm and 1.64±3.06mm depending on the software used). The higher standard deviations seen using both the White LED SL and ISL scanners used in this study compared to [19] are likely due to the fact that a subject was scanned rather than a stationary torso cast.

Obtaining patient torso geometries using handheld scanners presents some limitations that affect the accuracy of the resultant mesh. The Peel 1 scanner resolution was set to 2mm (compromising the maximum resolution - 0.5mm) to reduce the processing time and minimize the effects of breathing and movement. Alternative scan parameters for the Peel 1 scanner should be explored to determine the accuracy across configurations. The effects of wearing a compression shirt influenced the generated torso geometries due to wrinkles and bridging of concave areas, although this limitation was there for all scanners and it was deemed more clinically relevant to obtain the geometries while the patient was wearing clothing. The repeatability analysis also had limitations as the analysis was based on 3D point cloud data due to the low statistical power of the ALD measures and repeatability was only assessed for each scanner/software combination due to the randomization of investigators performing the scans that was adopted to avoid user bias. Increasing the number of markers positioned on the torso and pelvis, as well as performing a larger number of scans per investigator and software/scanner combination would have increased the statistical power of the data collected.

Since there was no true reference, in order to analyse the accuracy of the scanners we selected one of the geometries obtained using the Peel 1 scanner as our reference. This geometry was chosen since it had the highest manufacturer reported accuracy, but it must be noted that the Peel 1 scan does not represent the true geometry. Using a geometry acquired by the traditional plaster-cast approach as the reference was considered but the inaccuracies associated with this method meant that it did not provide advantages over using the Peel 1 scanner as the reference. Future work will focus on exploring the accuracy of scoliosis braces created using low-cost handheld scanners compared to the plaster-cast method and overcome the technical challenges associated with digital design and additive manufacturing of scoliosis braces.

Conclusions

Low-cost ISL and AS scanners such as the ST01 and Mark II provide high accuracy and repeatability with small differences in terms of anatomical landmark distances and torso surface deviations when compared to a high-resolution and considerably higher cost SL scanner (Peel 1). Phone-photogrammetry has even lower cost but has poor accuracy, and takes a long time to generate torso meshes, therefore is not suited to this application. The mesh generation software used has little effect on the accuracy or repeatability and therefore should be chosen with cost and usability in consideration to ensure it best suits the orthotist needs. Subject's breathing and movement resulted in surface deviations in the abdominal and anterolateral side regions of the torso and therefore these inaccuracies should be considered when using geometry captured with 3D scanners to design scoliosis braces.

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Figure captions

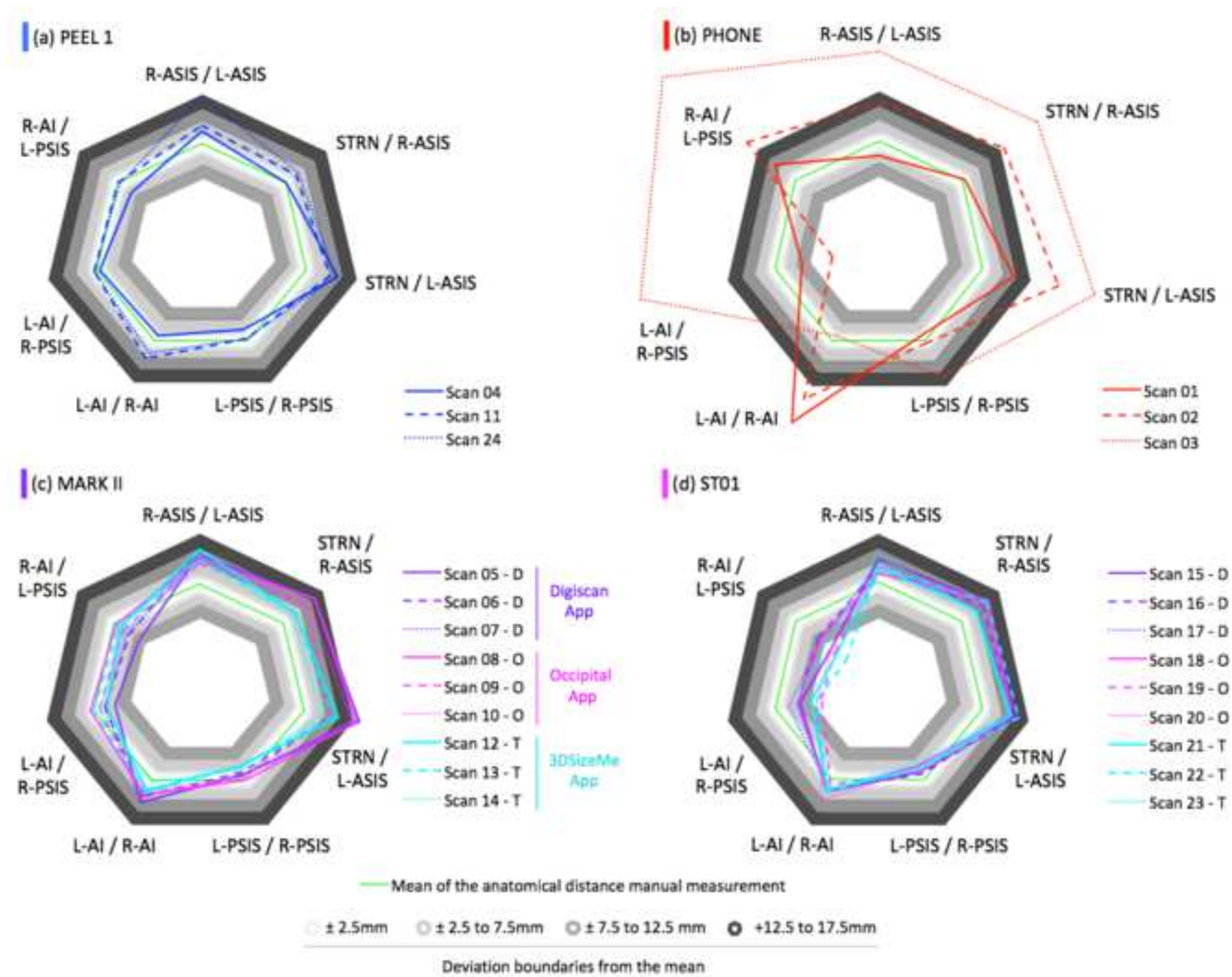
Figure 1 Landmark distance measures and surface deviation comparisons. (a) and (b) show anterior landmark distances (red lines) for scan 9 (Mark II/App O) and scan 24 (Peel 1), respectively. (c) shows the raw scan 4 (Peel 1) and the marker parts (red) overlapping mesh voids. (d) the anterior and (h) the posterior view of the subject during the scanning process showing the position of the markers. Note markers are shown here in black so they are visible but were painted white for the scanning. (e) shows scan 24 (Peel 1) used as the reference scan for surface map comparisons, (f) shows scan 10 (Mark II/App O), and (g) shows the surface deviation plot comparing (e) and (f) using CloudCompare.

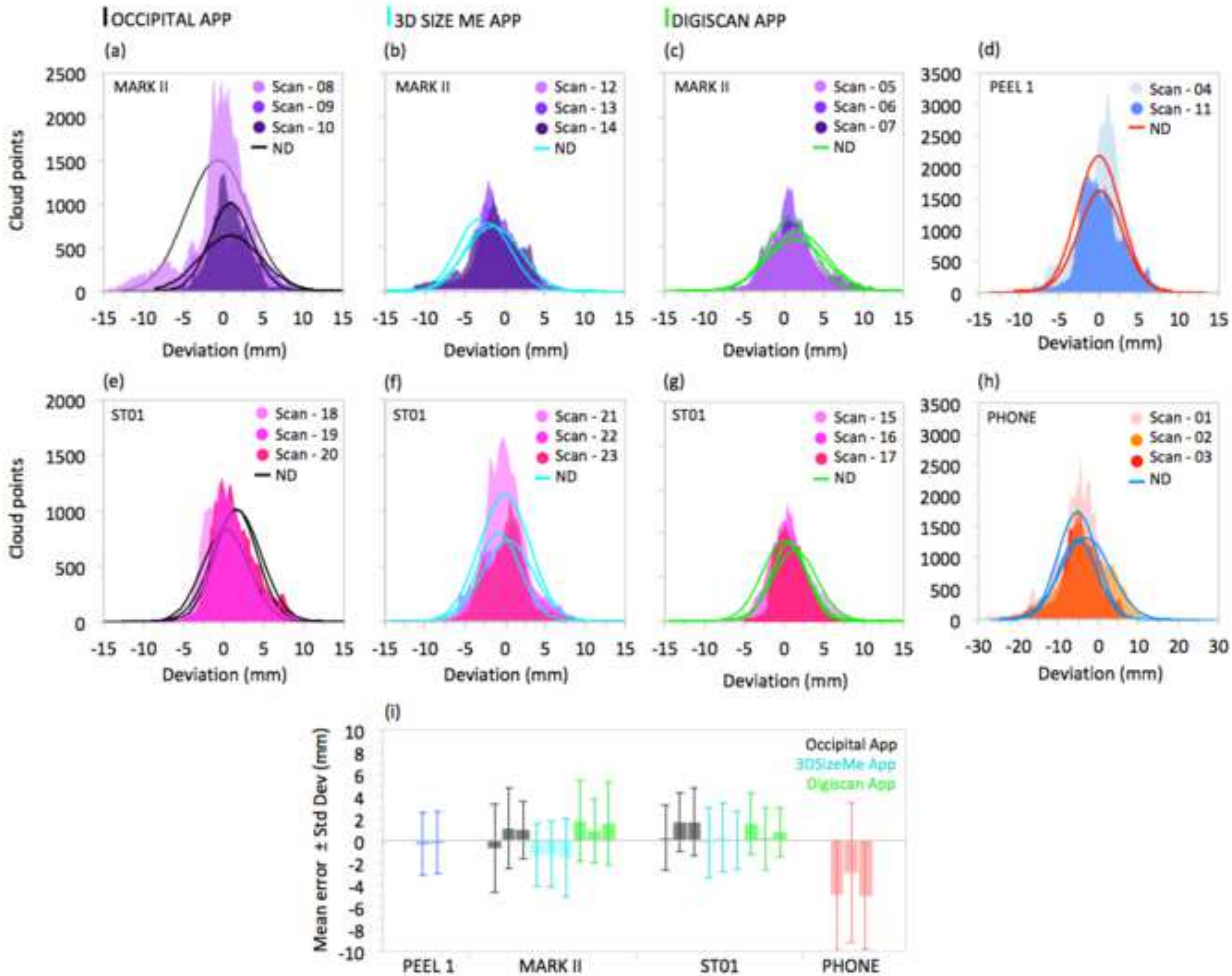
Figure 2 Deviations between anatomical landmark distances (ALDs) measured from torso meshes generated for each scanner and software/app combination and the manual ALD measurements (green polygon). (a) Peel 1, (b) phone-photogrammetry, (c) Mark II and (D) ST01. Note (c) and (d) include results from different applications (T-3DsizeMe, O-Occipital and D-Digiscan).

Figure 3 A comparison of mean anatomical landmark distances (ALDs) for the manual measurements (green horizontal lines with error bars in black) and the corresponding mean for each scanner. Note data from all three pieces of software/apps are combined for the ST01 and Mark II (MII) values presented in each graph. Error bars represent max/min values.

Figure 4 3D surface deviation maps. Deviation between the reference scan (Peel 1 – scan 24) and (a) Mark II scans (5-14), (b) ST01 scans (15-23), (c) Peel 1 scans (4 and 11), and (d) phone-photogrammetry scans (1-3).

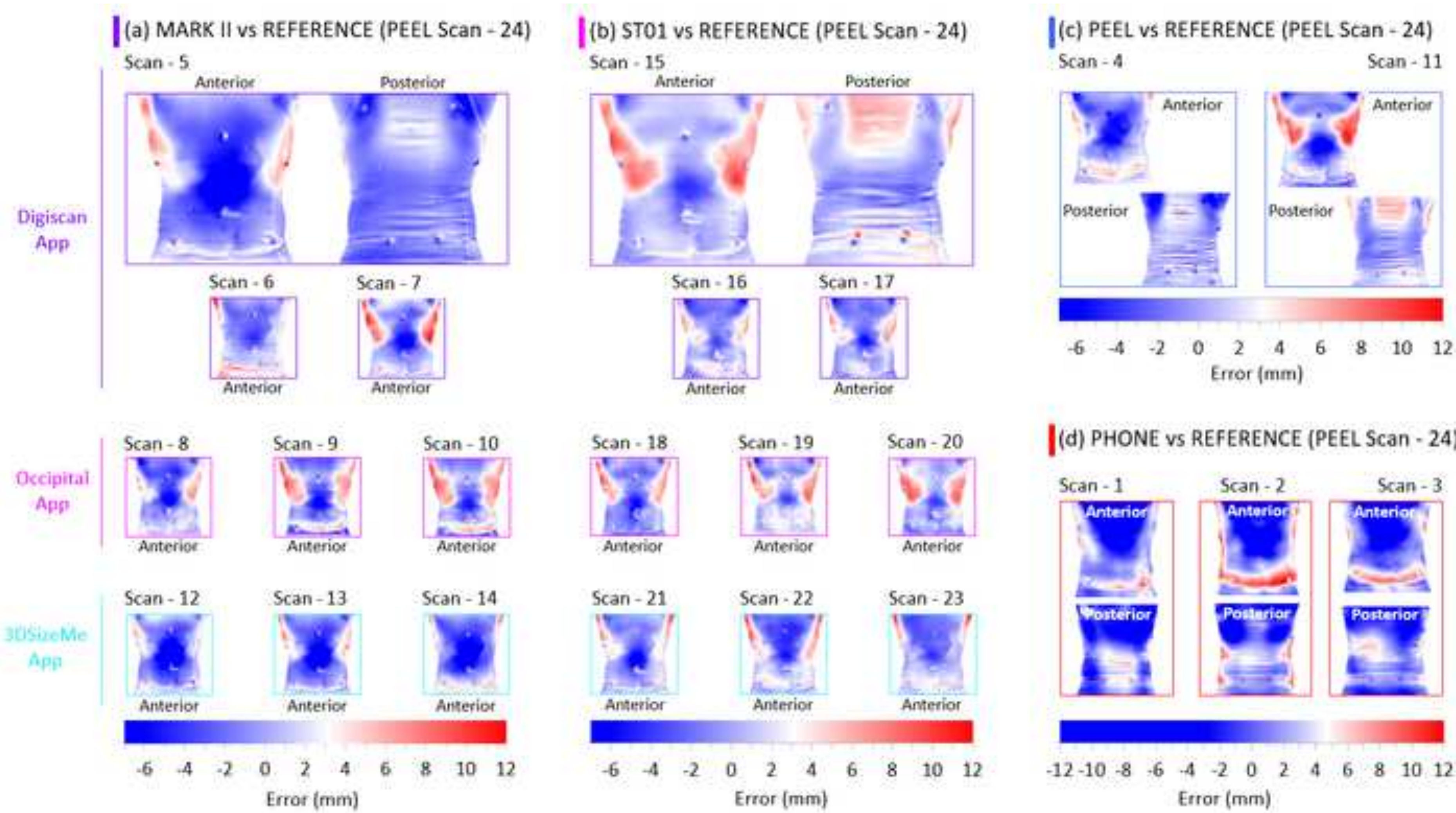
Figure 5 Histograms and normal deviation (ND) fit for the 3D surface deviation results with respect to the reference scan (Peel 1 – scan 24). (a-c) show results for the Mark II scanner using (a) the Occipital app, (b) the 3DSizeMe app, and (c) the Digiscan app. (d) shows results for the Peel 1 scanner (note just scan 4 and 11 are shown since scan 24 was used as the reference scan). (e-g) shows results for the ST01 scanner using (e) the Occipital app, (f) the 3DSizeMe app and (g) the Digiscan app. (h) shows results for the phone-photogrammetry scans. (i) shows mean errors from the reference scan (Peel 1 – scan 24) for each scan made with each scanner and software/app combination.


(a) PEEL 1
R-ASIS / L-ASIS
STRN / R-ASIS
STRN / L-ASIS
L-PSIS / R-PSIS
L-AI / R-AI
L-AI / R-PSIS
R-AI / L-PSIS
Scan 04
Scan 11
Scan 24
(b) PHONE
R-ASIS / L-ASIS
STRN / R-ASIS
STRN / L-ASIS
L-PSIS / R-PSIS
L-AI / R-AI
L-AI / R-PSIS
R-AI / L-PSIS
Scan 01
Scan 02
Scan 03
(c) MARK II
R-ASIS / L-ASIS
STRN / R-ASIS
STRN / L-ASIS
L-PSIS / R-PSIS
L-AI / R-AI
L-AI / R-PSIS
R-AI / L-PSIS
Scan 05 - D
Scan 06 - D
Scan 07 - D
Digiscan App
Scan 08 - O
Scan 09 - O
Scan 10 - O
Occipital App
Scan 12 - T
Scan 13 - T
Scan 14 - T
3DSizeMe App
(d) ST01
R-ASIS / L-ASIS
STRN / R-ASIS
STRN / L-ASIS
L-PSIS / R-PSIS
L-AI / R-AI
L-AI / R-PSIS
R-AI / L-PSIS
Scan 15 - D
Scan 16 - D
Scan 17 - D
Scan 18 - O
Scan 19 - O
Scan 20 - O
Scan 21 - T
Scan 22 - T
Scan 23 - T
Mean of the anatomical distance manual measurement
± 2.5mm
± 2.5 to 7.5mm
± 7.5 to 12.5 mm
+12.5 to 17.5mm
Deviation boundaries from the mean



OCCIPITAL APP
3D SIZE ME APP
DIGISCAN APP
(a)
MARK II
Scan - 08
Scan - 09
Scan - 10
ND
Cloud points
Deviation (mm)
(b)
MARK II
Scan - 12
Scan - 13
Scan - 14
ND
Deviation (mm)
(c)
MARK II
Scan - 05
Scan - 06
Scan - 07
ND
Deviation (mm)
(d)
PEEL 1
Scan - 04
Scan - 11
ND
Deviation (mm)
(e)
ST01
Scan - 18
Scan - 19
Scan - 20
ND
Cloud points
Deviation (mm)
(f)
ST01
Scan - 21
Scan - 22
Scan - 23
ND
Deviation (mm)
(g)
ST01
Scan - 15
Scan - 16
Scan - 17
ND
Deviation (mm)
(h)
PHONE
Scan - 01
Scan - 02
Scan - 03
ND
Deviation (mm)
(i)
Mean error ± Std Dev (mm)
Occipital App
3DSizeMe App
Digiscan App
PEEL 1
MARK II
ST01
PHONE

Figure_4


(a) MARK II vs REFERENCE (PEEL Scan - 24)
(b) ST01 vs REFERENCE (PEEL Scan - 24)
(c) PEEL vs REFERENCE (PEEL Scan - 24)
(d) PHONE vs REFERENCE (PEEL Scan - 24)
Digiscan App
Occipital App
3DSizeMe App
Scan - 5
Anterior
Posterior
Scan - 6
Scan - 7
Scan - 15
Scan - 16
Scan - 17
Scan - 4
Scan - 11
Scan - 8
Scan - 9
Scan - 10
Scan - 18
Scan - 19
Scan - 20
Scan - 12
Scan - 13
Scan - 14
Scan - 21
Scan - 22
Scan - 23
Scan - 1
Scan - 2
Scan - 3
-6 -4 -2 0 2 4 6 8 10 12
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12
Error (mm)

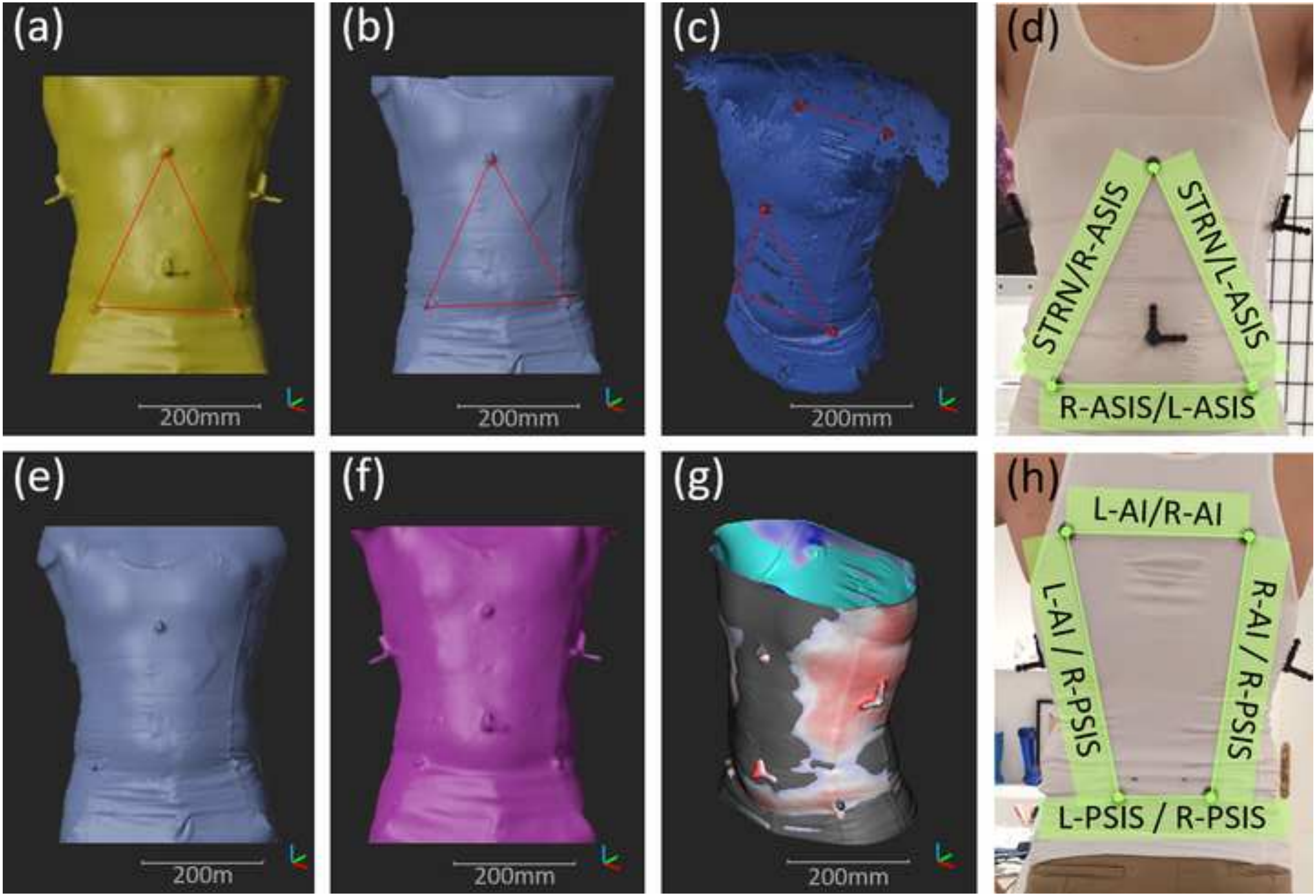
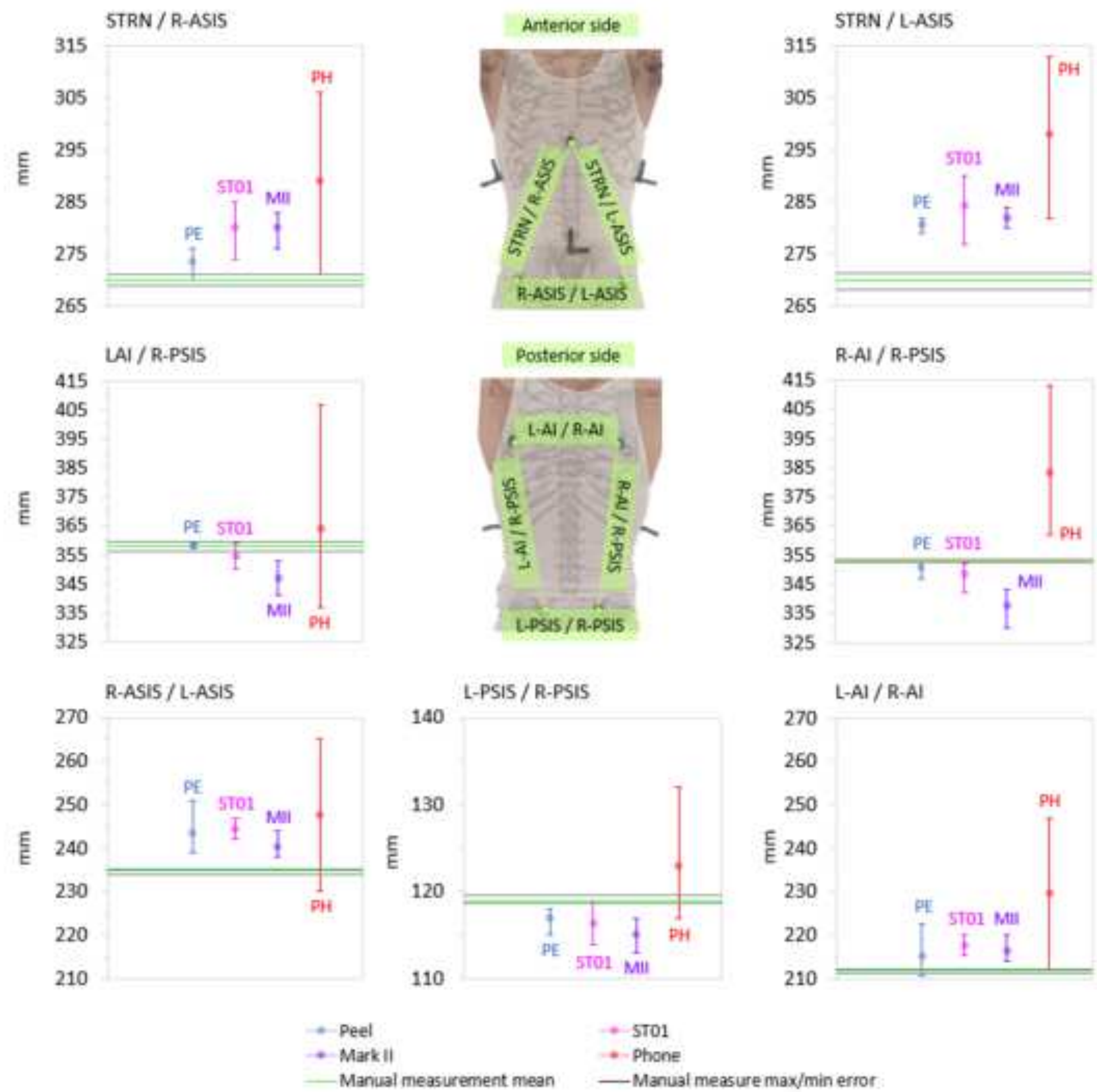

(a)
200mm
(b)
200mm
(c)
200mm
(d)
STRN/R-ASIS
STRN/L-ASIS
R-ASIS/L-ASIS
(e)
200m
(f)
200mm
(g)
200mm
(h)
L-AI/R-AI
L-AI / R-PSIS
R-AI / R-PSIS
L-PSIS / R-PSIS

Figure_3



STRN / R-ASIS
Anterior side
STRN / L-ASIS
R-ASIS / L-ASIS
LAI / R-PSIS
Posterior side
R-AI / R-PSIS
L-AI / R-AI
L-AI / R-PSIS
L-PSIS / R-PSIS
R-ASIS / L-ASIS
L-PSIS / R-PSIS
L-AI / R-AI
mm
PE
ST01
MII
PH
Peel
Mark II
ST01
Phone
Manual measurement mean
Manual measure max/min error

Table 1. Characteristics of the scanners.

Scanner	Manufacturer	Technology	Max Accuracy	Resolution	Software	Cost
Peel 1	Creaform Inc., Canada	White LED Structured light (SL)	0.25mm	0.5mm	Peel 3d	$6000
Structure Sensor Mark II	Occipital Inc., USA	Active Stereo (AS)	Not stated	1280x960 pixels	Digiscan, Scanner, 3DSizeMe	$530
Structure Sensor ST01	Occipital Inc., USA	Infrared Structured Light (ISL)	0.5mm	640x480 pixels	Digiscan, Scanner, 3DSizeMe	$380
Samsung SM-G960F	Samsung Electronics Co. Ltd., South Korea	Photogrammetry	Not stated	12.0 Megapixel	Meshroom	$0 (software)

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Table 3. Surface deviations between the reference scan (Peel 1 – scan 24) and each scanner and mesh generation software combination (mean, standard deviations and 95% confidence intervals (CI) of the mean and standard deviations). Note the distance between max. and min. mean surface deviation was used as an indication of repeatability, with a lower number representing better repeatability.

Scanner	**Software**	**Scan ID**	**Mean (mm)**	**95% CI**	**Std. Dev (mm)**	**95% CI**	**Distance between max. and min. mean surface deviation (mm)**
Peel 1	Peel 3D	4	-0.35	(-0.36, -0.34)	2.82	(2.81, 2.82)	0.14
		11	-0.21	(-0.22, -0.19)	2.80	(2.79, 2.80)	
Mark II	Digiscan App	5	1.74	(1.69, 1.78)	3.63	(3.60, 3.66)	0.92
		6	0.82	(0.79, 0.85)	2.87	(2.85, 2.89)	
		7	1.51	(1.47, 1.56)	3.73	(3.69, 3.76)	
	Occipital App	8	-0.71	(-0.73, -0.69)	3.98	(3.96, 3.99)	1.80
		9	1.09	(1.05, 1.12)	3.77	(3.75, 3.80)	
		10	0.93	(0.90, 0.95)	2.59	(2.58, 2.61)	
	3DSizeMe App	12	-1.33	(-1.36, -1.29)	2.87	(2.85, 2.89)	0.34
		13	-1.22	(-1.25, -1.19)	3.00	(2.98, 3.03)	
		14	-1.56	(-1.60, -1.53)	3.55	(3.52, 3.58)	
ST01	Digiscan App	15	1.50	(1.46, 1.53)	2.76	(2.73, 2.78)	1.37
		16	0.13	(0.09, 0.16)	2.80	(2.78, 2.83)	
		17	0.74	(0.71, 0.76)	2.24	(2.23, 2.26)	
	Occipital App	18	0.22	(0.19, 0.25)	2.92	(2.89, 2.94)	1.42
		19	1.62	(1.59, 1.65)	2.63	(2.61, 2.65)	
		20	1.64	(1.61, 1.67)	3.06	(3.04, 3.08)	
	3DSizeMe App	21	-0.21	(-0.25, -0.18)	3.16	(3.14, 3.19)	0.52
		22	0.31	(0.28, 0.35)	3.14	(3.12, 3.17)	
		23	0.02	(0.00, 0.05)	2.65	(2.63, 2.67)	
Phone	Meshroom	1	-4.97	(-5.01, -4.92)	4.95	(4.92, 4.98)	2.15
		2	-2.91	(-2.96, -2.86)	6.32	(6.29, 6.36)	
		3	-5.06	(-5.10, -5.02)	4.79	(4.77, 4.82)	

Table 2. Mean Absolute Error (MAE) of the anatomical landmark distance (ALD) between the manually measured distances and the ALDs measured from torso meshes from each combination of scanner and mesh generation software/app.

			Peel 1		**Structure Sensor Mark II**						**Structure Sensor ST01**						**Phone**	
	Software		3D		Scanner		3DSizeM		Digiscan		Scanner		3DSizeM		Digiscan		Meshroom	
	ALD error (mm)	Manual measure	MAE	SD	MAE	SD	MAE	SD	MAE	SD	MAE	SD	MAE	SD	MAE	SD	MAE	SD
Anterior	STRN / R-ASIS	270±1	3.7	3.2	12.7	2.1	5.3	1.2	12.0	5.2	12.0	1.0	8.3	3.2	10.0	2.0	1.0	0.0
	STRN / L-ASIS	270±2	10.7	1.5	16.0	5.3	10.3	3.1	17.0	5.3	12.3	1.5	11.7	2.1	12.3	0.6	28.0	15.5
	R-ASIS/L-ASIS	235±1	8.7	6.4	8.0	1.0	10.0	2.0	10.3	1.5	3.7	1.2	6.3	2.3	6.3	1.5	16.0	12.8
Posterior	L-AI / R-AI	212±1	4.7	2.5	5.3	1.2	3.3	2.1	8.3	1.2	5.0	3.0	4.3	0.6	4.3	0.6	19.0	15.4
	L-AI / R-PSIS	358±2	1.0	0.0	2.7	2.1	2.3	2.5	5.3	2.3	13.3	4.7	11.7	4.2	7.3	2.1	26.7	20.1
	R-AI / L-PSIS	353±1	2.3	3.2	2.3	1.5	3.3	1.5	8.0	2.6	15.0	3.6	18.3	5.0	12.3	3.2	30.3	26.5
	L-PSIS / R-PSIS	119±1	2.0	1.7	0.7	0.6	4.7	0.6	2.3	0.6	4.0	1.0	4.7	1.2	3.0	1.0	5.3	6.7
	All distances combined (mm)		4.7	*3.6*	6.8	*5.7*	5.6	*3.3*	9.0	*4.7*	9.3	*4.9*	9.3	*5.0*	8.0	*3.7*	18.0	*11.4*
	All distances combined (%)		1.8	*1.4*	2.6	*2.2*	2.2	*1.3*	3.5	*1.8*	3.6	*1.9*	3.6	*1.9*	3.1	*1.4*	7.0	*4.4*
	Mean scanning time		119±19s		47±7s		40±4s		26±2s		45±4s		31±3s		23±2s		160±35s	
	Mean mesh generation time		38±13min		11±7s		8±3s		7±2s		9±1s		10±4s		9±1s		105±35min	