



## Full length article

## Development of a new 360-degree surface topography application

R. Michalik<sup>a,\*</sup>, H. Siebers<sup>a</sup>, J. Eschweiler<sup>a</sup>, V. Quack<sup>a</sup>, M. Gatz<sup>a</sup>, T. Dirrachs<sup>b</sup>, M. Betsch<sup>a</sup><sup>a</sup> Department of Orthopaedics, University Hospital RWTH Aachen, Aachen, Germany<sup>b</sup> Department of Diagnostic and Interventional Radiology, University Hospital RWTH Aachen, Aachen, Germany

## ARTICLE INFO

## Keywords:

Surface topography  
Spine  
Posture  
Scoliosis  
Rasterstereography  
Whole-body scanner

## ABSTRACT

**Background:** Surface-topography has been used for almost two decades in the radiation-free clinical evaluation of spinal posture. So far, it was limited to the analysis of back surface and spine. In order to better understand, diagnose and treat complex spinal pathologies, it is important to measure the whole torso.

**Research question:** Purpose of this study was to introduce and test an application that allows 360° reconstruction and analysis of the patient's torso.

**Methods:** The application uses the information gathered from eight distinct scans and angles. For validation we used an Alderson phantom as an anthropomorphic body. Defined areas and volumes were measured by CT and surface-topography. Inter- and intra-rater reliability was tested in 35 healthy subjects by two observers.

**Results:** The results revealed good correspondence between systems in the imaging and evaluation of the Alderson model (5.3–0.5%). Inter- (0.9–0.98) and intra-rater reliability (0.8–0.95) testing revealed good and excellent results in the detection of almost all body surface structures and measurement of areas and volumes. Only area and volume measurements using jugular notch as a reference showed partly moderate results in reliability (0.62–0.93) testing.

**Significance:** We were able to introduce a novel 360° torso scan application using surface topography to reconstruct torso measurements. The results of our study showed its high validity and reliability. In the future, this application needs to be tested in patients with spinal pathologies. In summary, this new application may help to better understand, diagnose and treat patients with pathologies of torso and spine.

## 1. Introduction

The diagnosis and treatment of patients with three-dimensional (3D) spinal deformities, e.g. scoliosis, hyperkyphosis, still requires whole-spine x-rays to assess the severity of the deformity and to initiate adequate treatment. Frequent radiographs of the spine are also necessary in adolescent patients with spinal deformities to provide the necessary therapeutic information of the growing spine [1]. Especially in young patients, the consequences of repeated whole-spine x-rays can be problematic as it can significantly increase the risk of thyroid-, breast-cancer, and leukemia [2]. The proper treatment of complex spinal pathologies, e.g. in adolescent scoliosis, is not solely determined by radiological measurements, such as the Cobb-angle, but it is also influenced by the deformity itself and its influence on the ribcage, sternum, thoracic volume, and lung capacity [1]. More and more, the patient's self-perception and body-image, which both can be significantly affected by scoliosis, hyperkyphosis or thoracic deformities, become important [3]. Young female adolescent patients with scoliosis are both physically and psychologically affected by breast asymmetry,

which can be caused by the spinal deformity [4]. Most standard imaging techniques, such as conventional x-rays, and supine CT-scans do not allow a visualization and quantification of such trunk asymmetries [5]. Surface topography can be used to address the limitations of current whole-body imaging modalities and spare ionizing radiation. The system is based on the mathematical principle of triangulation [6,7]. It projects horizontal light lines onto the body surface of the patients. Then, a digital video camera captures an image of the body and the respective parallel light lines, which are distorted by the patients' anatomy. Based on the localization of specific anatomical landmarks a 3D-model of the spine and pelvis can be calculated. The 3D-spine-model is based on a correlation model of reference radiographs for an accurate 3D-reconstruction [8,9]. Previous studies showed good correlation with radiographic measurements of the spine in healthy subjects [10] and in patients with scoliosis [11,12]. Furthermore, the high accuracy and reliability was also shown under dynamic conditions [13–15]. Over the past years, surface topography has helped to reduce the number of x-rays needed to treat patients with spinal pathologies and has added valuable 3D information to better understand and treat spinal

\* Corresponding author at: Department of Orthopaedics, University Hospital RWTH Aachen, Pauwelsstraße 30, 52074, Aachen, Germany.

E-mail address: [rmichalik@ukaachen.de](mailto:rmichalik@ukaachen.de) (R. Michalik).

deformities [11,16]. So far, surface topography is limited to measure and reconstruct the back surface and spine of patients. However, spinal pathologies are 3D-deformities that not only affect the spine, but also the whole body. To overcome current limitations of this technique, a new surface topography application called “torso scan” that allows a 3D-reconstruction of the entire torso was developed. Purpose of this study was to introduce and evaluate a novel surface topography application for its validity and reliability in healthy subjects.

## 2. Methods

### 2.1. Surface topography-based torso scan application

The “Torso Scan” is a new developed application, using the surface topography system “Formetric” (Formetric 4D, Diers International GmbH, Schlangenbad, Germany). The “Torso Scan” application was developed along with this study to allow an three-dimensional and volume-related evaluation of the torso.

### 2.2. Human participants

35 healthy subjects (male = 27, female = 8) participated in this study. None of the participants had any history of spine, pelvic, torso or lower limb pathology. The study was approved by the local ethics committee (Study number: EK080/17) and all subjects gave their written and oral consent.

### 2.3. Measurement protocol and data acquisition

#### 2.3.1. Torso scan protocol

The “Torso scan” application combines eight individual surface topography images from eight previously defined angles in order to be able to create a continuous digital 3D-model. Subjects were standing in a relaxed posture, with arms hanging to the sides and extended knees to ensure reproducible measurements. Subjects positioned themselves in eight predefined positions relative to the camera: 0° (full back), then in a clockwise rotation the 30°, 90°, 120° position, full frontal view (180°), 210°, 270° and 330° position (Fig. 1). Acquisition time was three seconds for each position. Afterwards the application automatically calculated the eight different 3D point-clouds from the different views of the body for further processing. By aligning two additionally placed shoulder markers, positioned slightly lateral and inferior to the acromion, the upper part of the volumetric torso scan was coarsely aligned.

For the final exact alignment of the eight individual point-clouds (creation of a single volumetric 3D model), surface features like curvature and surface normal vectors of all the eight surfaces models were matched to create a best-fit surface [17,18].

#### 2.3.2. Validity testing

In order to validate the “Torso scan”, we used an Alderson phantom (RANDO® Phantom, Alderson Research Laboratories Inc., Stamford, CT, USA), which has been previously applied in clinical routine to plan the radiation field for radiotherapy [19]. This model contains a human skeleton, which is embedded in isocyanate rubber. It provides a human-like surface, and also contains radiographically detectable bony structures. For validation we compared surface topography measurements of the Anderson model with CT scans. Flat infrared reflective markers were placed on the models back ( $n = 5$ : X1–X5) along the spinal midline starting from the cervical spine down to the thoracic and lumbar spine (Fig. 2). Additionally, markers were placed on the phantoms front. They were localized at the jugular notch (JN), lower sternum (ST), left and right nipple (NL, NR). The prepared model was placed on a rotating platform in order to position the model for the respective eight surface scans (Fig. 2). A series of three scans was performed each by two observers (OB1 and OB2) in alternating order. Afterwards we prepped the Phantom for CT measurements. The infrared reflective markers were accurately covered by crosshair CT spots (CT-SPOTS® crosshair, Beekley Medical®, Bristol, USA). The Alderson phantom underwent a standardized complete CT-scan on a dedicated 256-slice multidetector CT-scanner (MDCT) (SOMATOM Definition Flash, Siemens, Forchheim, Germany). The following scan parameters were used: 120 kV, effective tube current-time product 108 mA, slice thickness 1.0 mm, rotation time 280 ms, pitch 0.9, and collimation  $64 \times 1.0$  mm. The field-of-view was adapted to the model’s physique, and a medium smooth convolution kernel (B30f) was chosen for image reconstruction. Coronal and sagittal reconstructions were acquired. The CT scans were measured by each observer independently 3 times for defined areas and volumes as described below.

We defined specific areas and volumes of the measured model to evaluate validity and reliability of the “Torso scan” application. A total of five markers were placed on the back surface (reflective markers for surface measurements and CT-spots for CT measurements) and four markers on the front surface of the Alderson model. Using the “Torso scan” application the location of the marker was automatically detected by the software, and an axial cut was placed through the torso model from the center of the reflective marker. The so defined area was then

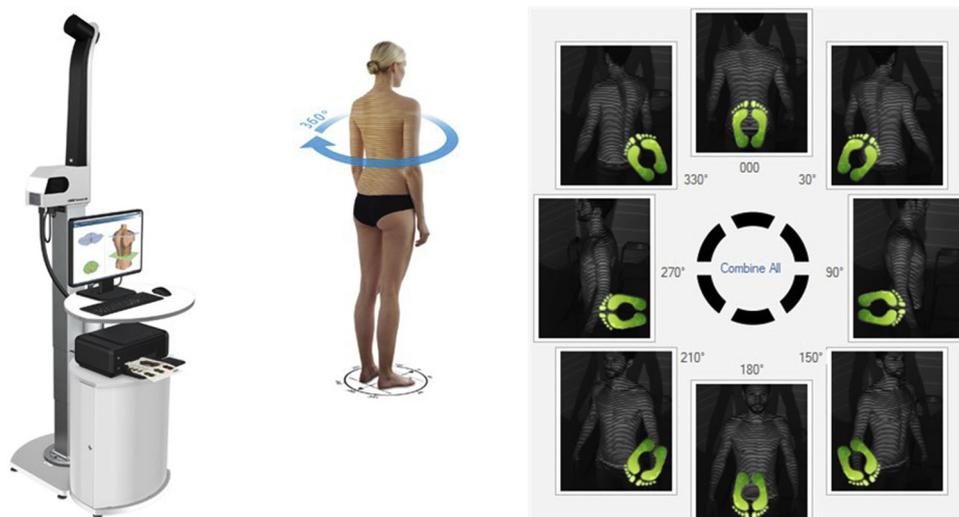
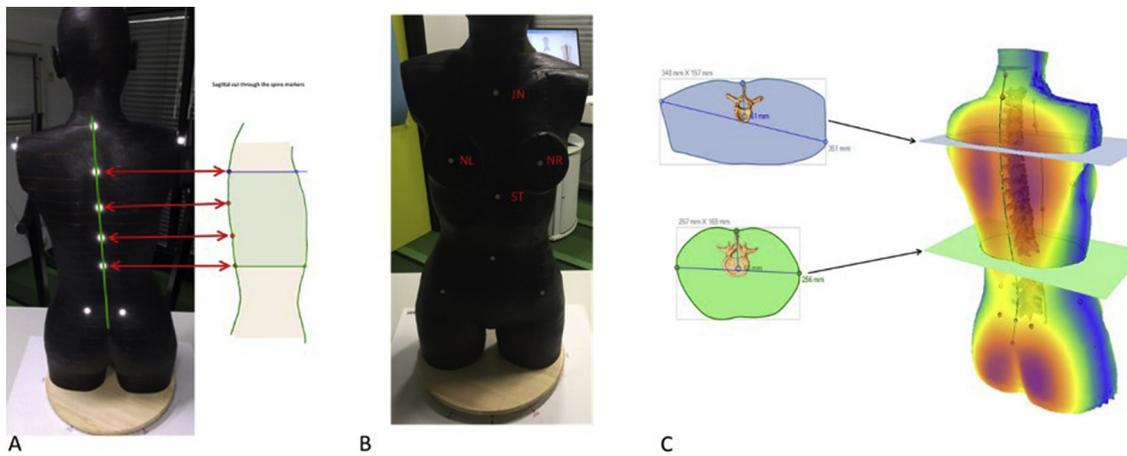
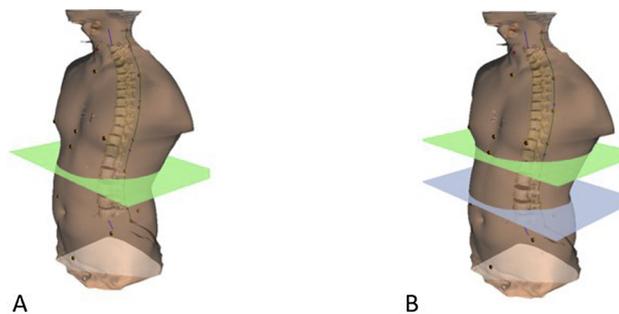


Fig. 1. The Torso-scan is a surface topography-based application. To create the three-dimensional torso model, 8 scans of the subject’s torso are taken from defined angles (Diers International GmbH, Schlangenbad, Deutschland).



**Fig. 2.** A) Alderson RANDO® Phantom placed on a platform, which can be rotated manually according to the underlying direction indicator. On the models back, reflective markers were placed on anatomical fixed points. The markers on the shoulders were used for the three-dimensional tracking of the model by the system. The sagittal profile shows the localization of posterior markers (X2–X5) used as intersection points for validation. B) Anterior Markers were placed approximately on the jugular notch (JN) left (NL) and right nipple (NR) and the distal sternum at the xiphoid process (ST). C) Strict axial cuts were made through the spinal phantom and the respective areas and volume between two markers were measured. The different colors define different surface heights (height map).



Areas and Volumes #000 T10 - L2: Volume = 8,02 Liter

Vertebra	Pos (mm)	Area (cm²)	VP	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	L1	L2
VP	279.00	133.70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T1	259.71	178.99	0.29	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T2	241.28	282.87	0.77	0.49	-	-	-	-	-	-	-	-	-	-	-	-	-
T3	221.50	414.97	1.42	1.14	0.65	-	-	-	-	-	-	-	-	-	-	-	-
T4	200.06	561.10	2.47	2.18	1.70	1.05	-	-	-	-	-	-	-	-	-	-	-
T5	177.18	702.31	4.01	3.73	3.24	2.59	1.54	-	-	-	-	-	-	-	-	-	-
T6	153.37	819.93	5.86	5.58	5.09	4.44	3.39	1.85	-	-	-	-	-	-	-	-	-
T7	128.67	900.66	7.95	7.66	7.18	6.53	5.48	3.94	2.09	-	-	-	-	-	-	-	-
T8	103.02	919.91	10.42	10.14	9.65	9.00	7.95	6.41	4.56	2.47	-	-	-	-	-	-	-
T9	76.40	879.54	12.88	12.59	12.10	11.46	10.41	8.86	7.01	4.93	2.46	-	-	-	-	-	-
T10	48.95	793.17	15.11	14.82	14.33	13.69	12.64	11.09	9.24	7.16	4.69	2.23	-	-	-	-	-
T11	20.54	698.27	17.10	16.81	16.32	15.67	14.62	13.08	11.23	9.14	6.67	4.22	1.99	-	-	-	-
T12	-8.62	646.62	19.07	18.79	18.30	17.65	16.60	15.06	13.21	11.12	8.65	6.20	3.97	1.98	-	-	-
L1	-39.44	618.62	20.97	20.68	20.19	19.55	18.50	16.95	15.11	13.02	10.55	8.09	5.86	3.87	1.89	-	-
L2	-74.03	582.93	23.13	22.84	22.35	21.70	20.65	19.11	17.26	15.17	12.70	10.25	8.02	6.03	4.05	2.16	-
L3	-112.27	578.03	25.19	24.91	24.42	23.77	22.72	21.18	19.33	17.24	14.77	12.32	10.09	8.10	6.12	4.23	2.07
L4	-154.03	612.87	27.69	27.41	26.92	26.27	25.22	23.68	21.83	19.74	17.27	14.82	12.59	10.60	8.62	6.73	4.57
DM	-202.60	659.46	30.96	30.67	30.18	29.54	28.49	26.94	25.09	23.01	20.54	18.08	15.85	13.86	11.88	9.99	7.83

**Fig. 3.** A) Axial cut through a Torso Scan 3D model of subject with spine reconstruction. B) Volumes are calculated between different cuts. C) The calculation and measurement of areas and volumes is automatically performed by the system.

automatically measured by the software application. Furthermore, volumes between the areas (X1–X2, X1–X3, X1–X4, X1–X5, JN–NL, JN–NR, JN–ST) were also automatically measured by the “Torso scan” application for validity testing. Similar to the surface topography measurements, we used the same protocol for the CT-measurements of the Alderson. First, the center of the CT-spots was localized on the CT-scans of the model in the sagittal reconstruction. Then, based on the position of the Alderson model on the CT-table, a strict axial cut was placed through the torso from the center of the CT-spots. For comparison, the area was then measured by two observers using JiveX DICOM Viewer Version 5.0 (VISUS Health IT GmbH, Bochum, Germany). Furthermore, we also measured the volume between the respective areas using 3D Slicer Version 4.8.1 [20] (Fig. 3).

**2.3.3. Reliability testing**

To test the reliability of the “Torso scan” application, we measured a total of 35 healthy subjects (Table 1). Infrared flat reflective markers were placed on each subjects’ back (spinous process of the 7th cervical body (VP) and both lumbar dimples) and front (Jugular notch = JN, Sternum = ST and both nipples = NL and NR). Each subject was scanned 3 times (every 5 min: t = 0, t = 5, t = 10, t = 15, t = 20, t = 25 min) by each observer (OB1 and OB2). The measurements were performed, following the torso-scan protocol. Areas and volumes were defined by five intersection points in the middle of the patient’s spine (C7 (X1), T5 (X2), T8 (X3), T11 (X4), L2 (X5)) for reference purposes. Also, four anterior intersection points were defined (JN, NL, NR, ST). Marking the intersection points was done automatically by the software of the system (Fig. 3). The accuracy of the automatic detection of the

**Table 1**  
Comparison of the values of the rasterstereographic “torso scan” application and CT measurements for the defined areas and volumes of the Alderson model.

Area	Value		Deviation	
	Torso-scan [cm <sup>2</sup> ]	CT [cm <sup>2</sup> ]	Absolute [cm <sup>2</sup> ]	Relative
X1	126.70 ± 5.72	125.41 ± 0.18	1.29	1.03%
X2	458.24 ± 3.00	460.76 ± 1.86	-2.53	-0.55%
X3	473.56 ± 0.67	479.21 ± 2.85	-5.66	-1.18%
X4	408.71 ± 4.62	418.19 ± 1.44	-9.48	-2.27%
X5	349.61 ± 2.56	355.16 ± 0.75	-5.55	-1.56%
JN	427.47 ± 11.07	436.61 ± 2.33	-9.14	-2.09%
NL	458.18 ± 2.20	466.72 ± 0.48	-8.55	-1.83%
NR	459.26 ± 2.52	469.83 ± 0.31	-10.57	-2.25%
ST	398.09 ± 7.11	399.77 ± 0.49	-1.68	-0.42%

Volume	Value		Deviation	
	Torso-scan [liter]	CT [liter]	Absolute [liter]	Relative
X1-X2	3.02 ± 0.11	3.19 ± 0.08	-0.17	-5.30%
X1-X3	6.61 ± 0.11	6.80 ± 0.08	-0.19	-2.82%
X1-X4	9.89 ± 0.12	10.35 ± 0.06	-0.46	-4.46%
X1-X5	12.69 ± 0.07	13.39 ± 0.02	-0.70	-5.25%
JN-NL	5.62 ± 5.52	5.52 ± 0.01	0.09	1.69%
JN-NR	5.55 ± 5.76	5.76 ± 0.01	-0.21	-3.66%
JN-ST	8.40 ± 0.09	8.59 ± 0.01	-0.19	-2.21%

spinous process, the vertebrae and the reflective marker by the used rasterstereographic device has been shown in previous studies [21,22]. The respective area and volume measurements were automatically calculated by the software itself (Fig. 3). The subjects were measured three times by two observers (OB1 and OB2). The intraclass-correlation-coefficient (ICC) was used to evaluate the intra-rater-reliability as well as the inter-rater-reliability. For the determination of the intra-rater-reliability the ICC-model “Two-way mixed, single score ICC (A,1)” (McGraw and Wong convention) was used to evaluate the degree of agreement among all three measurements performed by one observer [23]. To determine the inter-rater-reliability and evaluate the degree of agreement among the two observers the ICC model “Two-way mixed, average score ICC (A,k)” (McGraw and Wong convention) is used.

#### 2.4. Statistics

Statistical analysis was performed using Matlab (Version 2018a, MathWorks® Inc., Natick, MA, USA) and SPSS software (IBM SPSS Statistics, Version 24, Chicago, IL, USA). All data were checked for Gaussian distribution by Shapiro Wilk test. According to this test and the central limit theorem, the dataset for the ICC-study was normally distributed. ICC results were graded in poor < 0.5, moderate 0.5–0.75, good 0.75–0.9, and excellent > 0.9. The Shapiro Wilk test shows that the distribution of the dataset of the Alderson phantom measurements does not follow a Gaussian distribution.

### 3. Results

#### 3.1. Validity measurements

Overall, the “Torso scan” area measurements showed a deviation from the CT measurements for the respective areas from -2.27% to 1.03% (-10.57 to 1.29 cm<sup>2</sup>) (Table 1). The highest deviation was found for the back area X4 with -2.27% (-9.48 cm<sup>2</sup>) and for the front area NR with -2.25% (-10.57 cm<sup>2</sup>) (Fig. 4). For the volumetric measurements of the Alderson phantom, we found comparable results. Here, we measured absolute differences between the “Torso scan” application and the CT measurements from -5.30% to 1.69% (Table 1). The highest relative deviation was found for the back area X1-X2 of -5.30% (-0.17 L) and for the front area JN-NR of -3.66% (-0.21 L)

(Fig. 4).

#### 3.2. Reliability measurements

The reliability measurements revealed almost no user dependent differences. Area evaluation based on the posterior intersection points revealed mostly excellent reliability (Table 2). The area at the intersection of marker X1 showed good intra-rater reliability (ICC < 0.9) in both observers (Table 2). All other areas referring to posterior intersection points (X2–X5) revealed excellent reliability in the evaluation done by both observers (ICC > 0.9). Areas evaluated based on anterior intersection points showed similar results (Table 2). The upper intersection point at marker JN revealed only moderate reliability (ICC: 0.622 and 0.667) in both observers. All other areas (NR, NL and ST) showed excellent reliability in observer 1 and 2 (ICC > 0.9). Inter-rater-reliability showed excellent results for almost all areas. However, the area located at intersection point of marker JN revealed good reliability between both observers (Table 2).

Evaluating the reliability of the measured volumes between the areas showed excellent results for the majority of volumes. Intra-rater reliability testing showed good results for the cervico-thoracic volume (X1–X2) based on posterior intersection points (X1–X2). All other volumes based on back markers, revealed excellent reliability in both observers (X1–X3, X1–X4 and X1–X5). Volumes calculated between anterior body markers showed good and moderate intra-observer reliability. However inter-observer reliability was excellent for all measured volumes (Table 2).

### 4. Discussion

Full body surface scanners are well established e.g. in the textile industry, where they are used to create custom-fit clothes [24]. In medicine, 3D body surface scanners are so far only used for anthropometric measurements and the crude analysis of the body shape [25–27]. However, these systems do not provide reliable information of the musculoskeletal system. Therefore, magnetic resonance imaging (MRI) and – especially in musculoskeletal imaging – computed tomography (CT) are still standard techniques to assess 3D deformities [28]. Although there do exist upright MRI-scanners, they are not readily available for functional imaging of such patients. The aim of this study was to introduce and evaluate a novel surface topography based “Torso scan” application. Rasterstereography has been used for evaluation of humans back surface and spine since many years. In previous studies, the accuracy of the here used spine model has been shown [11,13–15]. Furthermore, the high accuracy and reliability of the automatic fix point and marker detection by surface topography was shown in multiple studies [13,21,22]. A pilot study by Knott et al. evaluated single anterior surface topography measurements of patients with torso deformities [29]. The system used, however was only able to measure the anterior or posterior torso, without the possibility to match and combine both scans to allow for a complete 3D-reconstruction. In addition, to conventional surface topography, which has been used in multiple previous studies [11,13–15], the here introduced “Torso scan” application does allow a 3D analysis and reconstruction of the whole torso. In order to test the validity of this new application, we compared “torso scan” measurements of torso with CT-scans as the current gold standard in musculoskeletal imaging. In summary, the results showed only minor differences for the measured areas and volumes compared to the CT-measurements. Areas measured by surface topography showed low relative deviations (0.42–2.25%) compared to the CT based measurements. In most cases the surface torso scans underestimated the areas. These findings were also shown for volumetric measurements. Some differences can be explained because of the dark, black color of the Alderson model, which decreased the contrast between the projected light lines and the surface of the model, and therefore led to difficulties in reconstructing the 3D-torso. Results of reliability testing showed

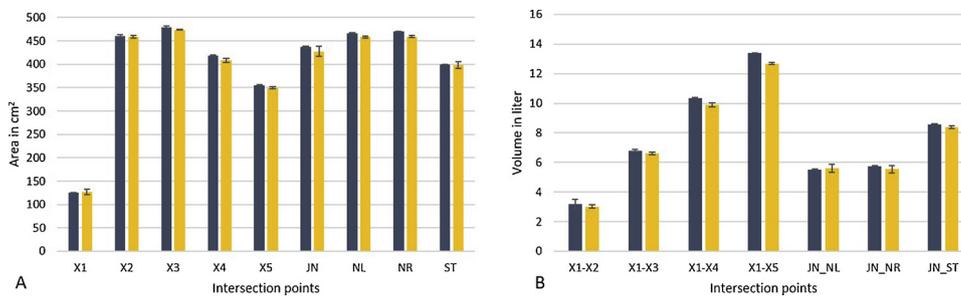


Fig. 4. Comparison of average values evaluated for Alderson-phantom measurements using CT scan (blue bars) and raster-stereography torso-scan application (yellow bars). Intersection points on back (X1-X5) and front (JN, NL, NR, ST) were used for the definition of the areas (A). Volumes were defined between the planes at the intersection points on back and front (B) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

**Table 2**  
The intra-rater-reliability (observer 1 and 2) and the inter-rater reliability of the rasterstereographic application “torso scan” for area and volume measurement.

Area	Intra-rater reliability		Inter-rater reliability
	Observer 1	Observer 2	
X1	0.875	0.801	0.906
X2	0.917	0.904	0.958
X3	0.934	0.934	0.978
X4	0.932	0.943	0.982
X5	0.944	0.942	0.987
JN	0.622	0.667	0.729
NL	0.919	0.91	0.982
NR	0.9	0.925	0.982
ST	0.924	0.884	0.976

Volume	Intra-rater-reliability		Inter-rater-reliability
	Observer 1	Observer 2	
X1-X2	0.876	0.857	0.927
X1-X3	0.915	0.918	0.965
X1-X4	0.935	0.942	0.981
X1-X5	0.941	0.951	0.985
JN-NL	0.782	0.669	0.924
JN-NR	0.818	0.819	0.955
JN-ST	0.782	0.669	0.924

mostly excellent intra- and interrater reliability. It is interesting to note that the reliability of areas measured in the cervicobrachial region revealed only moderate or good reliability. The named areas were calculated around JN and VP. The higher differences between the two systems might be related to frequent movements of shoulder girdle and throat, that occurred even under standing in a relaxed posture. The findings for volume measurements showed similar results. Intra-rater reliability for volumes based anterior measurements revealed to be moderate or good, while measurements from posterior points were mostly excellent. However, inter-observer reliability proved to be excellent for all calculated volumes. The reliability testing and automatic fix-point detection of the established spine model used in “Formetric” surface topography revealed similar results regarding reliability testing [21,22]. However, a 3D reconstruction and measurement of the entire torso by surface topography has not been described or evaluated before. Most 3D body surface-scanners on the market are based on laser scanning and are clinically used for anthropometric measurements regarding body shape and composition [25,30]. In a validation and calibration study of Shepherd et al. tape measurements were used for validation purposes of the hip and waist, which showed similar accuracy to our study [25]. However, to our knowledge, so far there is no light-based 3D whole body scanner that can be used for clinical indications like the imaging of 3D torso deformities. Surface topography was initially developed to image spine and torso deformities without any harmful radiation and to gain a better understanding of such complex deformities. With the development of the “Torso scan” application, this technique does now potentially offer clinicians and scientists new aspects and perspective to analyze torso and spinal

deformities [11,29]. It was recently shown that surface topography can detect anterior trunk asymmetry for the assessment of patients with scoliosis [29]. The use of the torso-scan may now allow to combine the anterior and posterior findings for a better understanding and therapeutic decision making. It was also shown that scoliotic patients pre-operative concern and postoperative satisfaction depend not only on radiographic measurable musculoskeletal deformation [3]. Soft tissue and surface irregularities that affect patients body image are often difficult to objectify and quantify. The combination of anthropometric and musculoskeletal imaging by the torso-scan, can be of great use in accessing and quantifying the patient’s own body image and asymmetries, such as e.g. shoulder height differences, breast asymmetry or rib cage deformities. It has to be mentioned that this pilot study uses healthy subjects for reliability testing as the recently developed torso scan has previously not been used or evaluated. As the torso-scan is mostly developed for diagnostic purposes in further studies it needs to be evaluated in patients with e.g. spine and chest wall deformities.

Our study has certainly some limitations. The results of our validity measurements are certainly distorted by the single number of objects measured. Further difficulties were caused by the black surface color of the Alderson phantom as the light-based surface topography systems depends on the reflection of the projected raster [6,7]. This also might have caused the slight but constant overestimation of measured areas and volumes compared to CT scan. However even under these challenging circumstances the “Torso scan” provides accurate automatic reconstruction of the used body. It must also be noted, that although CT-measurements were considered to be gold standard, all CT-measurements were done semi-automatically by the observers. This might have also led to some differences in the results between the two systems. Previous studies showed the reliability of dynamic surface topography measurements for the analysis of the spine and pelvis under physiological and pathological conditions [13–15].

The “torso scan” application, however, provides valuable additional information of the whole torso. So far, this application is limited to the standing position due to the use of a single camera system. As we were able to prove excellent reliability and validity of this system, we aim to develop a two-camera system to allow a whole-body analysis under dynamic conditions.

**5. Conclusions**

In this study, we were able to show and demonstrate a novel “torso scan” application, which does allow the reconstruction of the torso with adequate accuracy and reliability. In the future, such an application will be helpful to better understand, visualize and treat spinal and thoracic deformities.

**References**

- [1] M.A. Asher, D.C. Burton, Adolescent idiopathic scoliosis: natural history and long term treatment effects, *Scoliosis* 1 (1) (2006) 2.
- [2] A.R. Levy, M.S. Goldberg, N.E. Mayo, J.A. Hanley, B. Poitras, Reducing the lifetime risk of cancer from spinal radiographs among people with adolescent idiopathic scoliosis, *Spine* (Phila. Pa. 1976) 21 (13) (1996) 1540–1547 discussion 1548.
- [3] J.D. Auerbach, B.S. Lonner, C.E. Crerand, S.A. Shah, J.M. Flynn, T. Bastrom, et al.,

- Body image in patients with adolescent idiopathic scoliosis: validation of the Body Image Disturbance Questionnaire—Scoliosis Version, *J. Bone Jt. Surg. Am.* 96 (8) (2014) e61.
- [4] F.C. Tsai, M.S. Hsieh, C.K. Liao, S.T. Wu, Correlation between scoliosis and breast asymmetries in women undergoing augmentation mammoplasty, *Aesthet. Plast. Surg.* 34 (3) (2010) 374–380.
- [5] G. Redding, K. Song, S. Inscore, E. Effmann, R. Campbell, Lung function asymmetry in children with congenital and infantile scoliosis, *Spine J.* 8 (4) (2008) 639–644.
- [6] B. Drerup, E. Hierholzer, Automatic localization of anatomical landmarks on the back surface and construction of a body-fixed coordinate system, *J. Biomech.* 20 (10) (1987) 961–970 <http://www.ncbi.nlm.nih.gov/pubmed/3693377>.
- [7] B. Drerup, E. Hierholzer, Objective determination of anatomical landmarks on the body surface: measurement of the vertebra prominens from surface curvature, *J. Biomech.* 18 (6) (1985) 467–474 <http://www.ncbi.nlm.nih.gov/pubmed/4030803>.
- [8] A.R. Turner-Smith, A television/computer three-dimensional surface shape measurement system, *J. Biomech.* 21 (6) (1988) 515–529 <http://www.sciencedirect.com/science/article/pii/0021929088902448>.
- [9] A.R. Turner-Smith, J.D. Harris, G.R. Houghton, R.J. Jefferson, A method for analysis of back shape in scoliosis, *J. Biomech.* 21 (6) (1988) 497–509 <http://www.sciencedirect.com/science/article/pii/0021929088902424>.
- [10] B. Drerup, E. Hierholzer, Evaluation of frontal radiographs of scoliotic spines—part I. Measurement of position and orientation of vertebrae and assessment of clinical shape parameters, *J. Biomech.* 25 (11) (1992) 1357–1362.
- [11] P. Knott, P. Sturm, B. Lonner, P. Cahill, M. Betsch, R. McCarthy, et al., Multicenter comparison of 3D spinal measurements using surface topography with those from conventional radiography, *Spine Deform.* 4 (2) (2016) 98–103.
- [12] B. Drerup, Rasterstereographic measurement of scoliotic deformity, *Scoliosis* 9 (2014) 22 <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4268794/>.
- [13] M. Betsch, M. Wild, B. Johnstone, P. Jungbluth, M. Hakimi, B. Kuhlmann, et al., Evaluation of a novel spine and surface topography system for dynamic spinal curvature analysis during gait, *PLoS One* 8 (7) (2013) e70581 <http://www.ncbi.nlm.nih.gov/pubmed/23894674>.
- [14] M. Betsch, M. Wild, P. Jungbluth, M. Hakimi, J. Windolf, B. Haex, et al., Reliability and validity of 4D rasterstereography under dynamic conditions, *Comput. Biol. Med.* 41 (6) (2011) 308–312 <http://www.ncbi.nlm.nih.gov/pubmed/21489425>.
- [15] A. Beeck, V. Quack, B. Rath, M. Wild, R. Michalik, H. Schenker, et al., Dynamic evaluation of simulated leg length inequalities and their effects on the musculoskeletal apparatus, *Gait Posture* 67 (2018) 71–76 <https://www.ncbi.nlm.nih.gov/pubmed/30292100>.
- [16] L. Hackenberg, E. Hierholzer, U. Liljenqvist, Accuracy of rasterstereography versus radiography in idiopathic scoliosis after anterior correction and fusion, *Stud. Health Technol. Inform.* 91 (2002) 241–245.
- [17] V. Nguyen, V. Nzomigni, C.V. Stewart, Fast and robust registration of 3D surfaces using low curvature patches, Second International Conference on 3-D Digital Imaging and Modeling (Cat. No. PR00062), (1999), pp. 201–208.
- [18] L. Tong, X. Ying, 3D point cloud initial registration using surface curvature and SURF matching, *3D Res.* 9 (3) (2018) 41, <https://doi.org/10.1007/s13319-018-0193-8>.
- [19] J.H. Kleck, J.B. Smathers, F.E. Holly, L.T. Myers, Anthropomorphic radiation therapy phantoms: a quantitative assessment of tissue substitutes, *Med. Phys.* 17 (5) (1990) 800–806.
- [20] A. Fedorov, R. Beichel, J. Kalpathy-Cramer, J. Finet, J.C. Fillion-Robin, S. Pujol, et al., 3D Slicer as an image computing platform for the Quantitative Imaging Network, *Magn. Reson. Imaging* 30 (9) (2012) 1323–1341.
- [21] L. Guidetti, V. Bonavolonta, A. Tito, V.M. Reis, M.C. Gallotta, C. Baldari, Intra- and interday reliability of spine rasterstereography, *Biomed Res. Int.* 2013 (2013) 745480 <http://www.ncbi.nlm.nih.gov/pubmed/23819119>.
- [22] M. Mohokum, S. Mendoza, W. Udo, H. Sitter, J.R. Paletta, A. Skwara, Reproducibility of rasterstereography for kyphotic and lordotic angles, trunk length, and trunk inclination: a reliability study, *Spine (Phila. Pa. 1976)* 35 (14) (2010) 1353–1358 <http://www.ncbi.nlm.nih.gov/pubmed/20505568>.
- [23] T.K. Koo, M.Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, *J. Chiropr. Med.* 15 (2) (2016) 155–163 <http://www.sciencedirect.com/science/article/pii/S1556370716000158>.
- [24] E. Bye, K.L. Labat, M.R. Delong, Analysis of body measurement systems for apparel, *Cloth. Text. Res. J.* 24 (2) (2006) 66–79.
- [25] B.K. Ng, B.J. Hinton, B. Fan, A.M. Kanaya, J.A. Shepherd, Clinical anthropometrics and body composition from 3D whole-body surface scans, *Eur. J. Clin. Nutr.* 70 (2016) 1265, <https://doi.org/10.1038/ejcn.2016.109>.
- [26] A.S. Jafari Roodbandi, H. Naderi, N. Hashemi-Nejad, A. Choobineh, M.R. Baneshi, V. Feyzi, Technical report on the modification of 3-dimensional non-contact human body laser scanner for the measurement of anthropometric dimensions: verification of its accuracy and precision, *J. Lasers Med. Sci.* 8 (1) (2017) 22–28 <https://www.ncbi.nlm.nih.gov/pmc/PMC5420361/> <https://www.ncbi.nlm.nih.gov/pubmed/28912940>.
- [27] A. Kuehnappel, P. Ahnert, M. Loeffler, A. Broda, M. Scholz, Reliability of 3D laser-based anthropometry and comparison with classical anthropometry, *Sci. Rep.* 6 (2016) 26672, <https://doi.org/10.1038/srep26672>.
- [28] N. Utkualp, I. Ercan, Anthropometric measurements usage in medical sciences, *Biomed Res. Int.* 2015 (2015) 7, <https://doi.org/10.1155/2015/404261>.
- [29] P. Knott, B. Lonner, M. Smith, E. Frommeyer, Y. Ren, Measuring anterior trunk deformity in scoliosis: development of asymmetry parameters using surface topography (a pilot study), *Scoliosis Spinal Disord.* 11 (Suppl. 2) (2016) 32.
- [30] N. Daniell, T. Olds, G. Tomkinson, Technical note: criterion validity of whole body surface area equations: a comparison using 3D laser scanning, *Am. J. Phys. Anthropol.* 148 (1) (2012) 148–155, <https://doi.org/10.1002/ajpa.22051>.