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Comparison of 3D Scanner Systems for Craniomaxillofacial Imaging

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Author contributions

PGMK, AB, and NRF designed the study, contributed to the data acquisition, analysis, and interpretation, and drafted the manuscript. CAAB contributed to the data acquisition, analysis, and interpretation, and critically revised the manuscript. RWFB, WR, and FA contributed to the data acquisition and critically revised the manuscript. OJ, SS, and DJD contributed to the data interpretation, and critically revised the manuscript.

Summary

Two-dimensional photographs are the standard for assessing craniofacial surgery clinical outcomes despite lacking three-dimensional (3D) depth and shape. Therefore, 3D-scanners have been gaining popularity in various fields of plastic and reconstructive surgery, including craniomaxillofacial surgery.

Head shapes of eight adult volunteers were acquired with four 3D scanners: 1.5T Avanto MRI, Siemens; 3dMDface System, 3dMD Inc.; M4D Scan, Rodin4D; and Structure Sensor, Occipital Inc. Accuracy was evaluated as percentage of data within a range of 2 mm from the 3DMDface System reconstruction, by surface-to-surface root mean square distances (RMS), and with facial distance maps. Precision was determined with RMS.

Relative to the 3dMDface System, accuracy was highest for M4D Scan (90% within 2 mm; RMS of 0.71 mm ± 0.28 mm), then Avanto MRI (86%; 1.11 mm ± 0.33 mm), and Structure Sensor (80%; 1.33 mm ± 0.46). M4D Scan and Structure Sensor precision were 0.50 mm ± 0.04 mm and 0.51 mm ± 0.03 mm.

Clinical and technical requirements govern scanner choice, however, 3dMDface System and M4D Scan provide high-quality results. It is foreseeable that compact, hand-held systems become more popular in the near future.

Keywords
3D surface scanning, 3D photography, plastic surgery, craniofacial surgery, maxillofacial surgery

Introduction

In plastic surgery, two-dimensional (2D) digital photographs have long been the standard for assessment of clinical outcomes [1-3]. Linear measurements, angles and ratios are obtained from lateral and frontal views of the face to indicate aesthetics [4]. However, 2D images lack appropriate three-dimensional (3D) facial depth and shape [5]. Therefore, face shape analysis with 3D surface scans has recently gained popularity [2,6]. For instance, 3D scanners have been employed to evaluate outcomes in rhinoplasty, orthognathic surgery, cleft lip and palate, and maxillomandibular distraction [3,7-10]. Reported advantages of 3D surface scans include high accuracy and precision, quick acquisition, non-invasiveness, the ability to rotate and view a 3D scan from all angles, the ability to track 3D changes pre- and postoperatively, 3D video-analysis, and improved surgeon and patient satisfaction [2,3,11]. The main disadvantage is their high cost due to a high purchase price, the need for a designated room for static camera systems, the requirement for appropriately trained personnel and powerful computers to acquire and handle the pictures [12-15]. In recent years, with increased computing power at decreased cost, new technologies such as hand-held scanning devices have entered the market at substantially lower price [16].

Various types of hand-held scanning systems are available, each with advantages and disadvantages. Structured light scanners project a pattern of visible or infrared light on a surface and infer the 3D shape from the distortion of the projected pattern [19]; this type of scanners is ‘active’: a light pattern is emitted and the distortion is observed. Stereophotogrammetry scanners compute a 3D shape from photographs of two or more cameras at different angles [3,20]; these systems are passive as the scanner picks up reflection from ambient light. Alternatively, volumetric methods may be used to compute 3D shapes from 2D slices, for example from computed tomography (CT) or magnetic resonance (MR) imaging data [21,22].

Our aim in this paper is to describe how various 3D scanning systems compare to each other, including passive and active systems, static and hand-held technologies, and systems of high and low cost, in terms of accuracy, precision, and usability. The focus is on craniomaxillofacial imaging, but the methodology finds application in other fields of plastic and reconstructive surgery.

Materials and methods

Participants

Eight adult, healthy volunteers (4F/4M; age 31±4 years, range 24–37 years) participated in this study, with no obvious craniofacial abnormalities. Institutional approval was obtained and all participants gave informed consent for image acquisition and scientific publication. The strengthening the reporting of observational studies in epidemiology (STROBE) were followed [23].

Data acquisition and processing

Four different scanners were employed for three-dimensional data acquisition: the 1.5T clinical MR Avanto scanner (Siemens Healthcare, Erlangen, Germany); the static 3dMDface System (3dMD Inc., Atlanta, GA, USA), a hybrid active/passive stereophotogrammetry/structured light system, consisting of an assembly of two modules with three digital cameras per module and a flash system (Heike et al., 2009); the hand-held M4D Scan (Rodin4D, Pessac, France) based on white LED structured light; and the Structure Sensor (Occipital Inc., San Fransisco, CA, USA), an iPad (4th generation, Apple Inc., Cupertino, CA, USA) accessory, based on infrared structured light, that adds a second camera, infrared LEDs, and infrared sensor to the iPad [16]. (Table 1, Figure 1).

MR scans and 3dMDface System scans were acquired by experienced clinical operators, whilst a single operator with 6 months experience in image acquisition using these technologies acquired all M4D Scan and Structure Sensor scans.

The image acquisition and 3D reconstruction process was as follows for each device:

a. A standard 3D head, T1-weighted Fast Low Angle Shot (FLASH) sequence with 1 mm slice thickness was used to obtain cross-sectional images in the MR scanner with the volunteer in a supine head and body position. Data were exported as digital imaging and communications in medicine (DICOM) files. 3D reconstructions were obtained using Mimics (Materialise, Leuven, Belgium) through one thresholding operation (lower threshold of 80, upper threshold maximum value), followed by a volumetric reconstruction and a wrap, and then saved as stereolithography (STL) files.
b. With the 3dMDface static camera, a slightly tilted backwards head position was adopted in order to capture the full chin area [12]. 3D reconstructions were automatically provided by 3dMDpatient software installed in a Macbook Pro (Apple Inc., Cupertino, CA, USA) connected to the cameras, and exported as wavefront object (OBJ) files. In addition to the surface mesh, texture (TIF) and locator (MTL) files were exported simultaneously.
c. Data with the M4D hand-held scanner were acquired with a still and neutral head position, i.e. a horizontal Frankfurt line, and with the operator moving the scanner around the volunteer. 3D reconstructions were automatically saved by dedicated software Vxelements 2.0 (Creaform Inc., Quebec, Canada) installed in a laptop (Dell Latitude E6540, Round Rock, TX, USA) and exported as STL files.

d. The Structure Sensor acquisition was performed as for the M4D hand-held scanner. Occipital Inc. "Scanner – Structure Sensor Sample" software was used to visualise and export the 3D automatic reconstructions as OBJ files.

The process for elaboration and analysis of the 3D reconstructions was the same for all image modalities, performed by the same operator, and divided in the following four main steps.

For each participant individually, OBJ or STL surface scans were loaded in 3-Matic (Materialise). Facial overlays were created using global and *N*-point registration and, if deemed necessary after one full iteration, using small manual rotation and translation. The aligned scans were exported as STL files.

Aligned STL files were imported into computer aided design software Rhinoceros (Robert McNeel & Associates, Seattle, WA, USA) (Figure 2, step 1). A plane was created based on the left and right tragus and the chin. A second plane was created orthogonally to the first plane, on the line between the left and right tragus (Figure 2, step 2). The facial area within these two planes (Figure 2, step 3) was considered to calculate mesh area, size, and thus density.

The aligned and cropped STL files were imported into Meshmixer (Autodesk, Inc., San Rafael, CA, USA), where voids were filled using standard 'Smooth MVC' settings, and surfaces were minimally smoothed using 'shape preserving' setting to deal with artefacts and noise (Figure 2, step 4).

Data analysis and statistics

Closest point distance vectors between scan pairs were computed using VMTK [24] (The Vascular Modeling Toolkit, Bergamo, Italy) jointly with Matlab (The MathWorks, Natick, MA, USA), and were visualised in ParaView [25] (Kitware, Clifton Park, NY, USA). Data analysis and statistical analysis were carried out in R (v. 3.3.0, R Foundation for Statistical Computing, Vienna, Austria).

Distance vectors describing differences in face shape were divided in four groups according to Aung et al. (1995)[26]: those with a deviation of 0 – 1 mm (highly reliable), between 1 – 1.5 mm (reliable), between 1.5 – 2 mm (moderately reliable), and greater than 2 mm (unreliable). Furthermore, 95% confidence intervals (CI) were computed and points outside the CI were deleted in order to deal with artefacts in the distance vectors. Some artefacts originated from surfaces that were difficult to capture, e.g. eyebrows.

Accuracy of the camera systems was determined by the ability of the camera to capture the facial shape in comparison to a reference shape (Table 2, study 1). The 3dMDface System was chosen as a reference shape because of its low operator dependence, low scanning time, high accuracy, and high precision [12,13,27,28]. For each participant individually, Root Mean Square distance (RMS) mean and standard deviation (SD) was calculated as the surface-to-surface distance of the reference scan to the scan of interest.

Precision, or repeatability, of the M4D Scan and Structure scan was determined by acquiring and analysing six scans per camera for one participant, with time intervals of 12 hours. Firstly, scan 1 was taken as reference and compared to scans 2 – 6 (5 scan pairs), and secondly, scan 6 was taken as a reference and compared to scan 1 – 5 (additional 5 scan pairs, 10 in total per camera) (Table 2, study 2). RMS mean and SD were computed for all 10 pairs. Furthermore, to quantify the post-processing error induced by the steps as laid out above and in Figure 2, the dataset of one participant was analysed five times successively as laid out in the steps above (Table 2, study 3).

Usability was assessed qualitatively by evaluating user-friendliness of the software, and based on operators' and participants' experiences.

The Mann-Whitney U test was employed for comparison of RMS. P-values < 0.05 were assumed to be of significance. Mean ± SD based on all 8 datasets is given unless stated otherwise.

Results

Scanner overview

Table 1 provides an overview of each scanner properties, including their imaging modality, mean mesh density in the facial area for 8 scans, and mean acquisition time for 8 scans. Acquisition time was the lowest for the 3dMDface System (1.5 ms), followed by the Structure Sensor (20 s), M4D Scan (30 s), and Avanto MRI (300 s, highly dependent on acquisition sequence). Mesh density, dependent on the processing software, was the highest for the 3dMDface System, followed by the Avanto MRI, M4D Scan, and Structure Sensor.

Accuracy

Figure 3 displays facial colourmaps of participant 6, representative for the cohort, in reference to the 3dMDface System scan, highlighting regional differences on the face. For Avanto MRI, deviations are visible in the jaw, cheek, and eyes. For M4D Scan, some deviations in the eyes and around the mouth are observed. Contrary to the Structure Sensor, which shows moderate agreement overall, the former two show good concordance in the nose, forehead, and chin area.

For the same participant, Figure 4 graphically displays the deviations of the M4D Scan colourmap, together with 1 mm and 2 mm bounds. Figure 5 shows the percentages of points that are highly reliable, reliable, moderately reliable, and unreliable. RMS was calculated as a means of quantifying the overall accuracy of each scan, shown in Table 3. RMS of the M4D Scan (0.71 mm ± 0.28 mm) was significantly better than the RMS of both Avanto MRI (1.11 mm ± 0.33 mm, $p = 0.008$) and Structure Sensor (1.33 mm ± 0.46 mm, $p = 0.008$). There was no significant difference in RMS of the Avanto MRI and Structure Sensor ($p = 0.15$).

Precision

Precision of the M4D Scan and Structure Sensor is shown in Table 4. Mean and standard deviation were 0.51 mm ± 0.04 mm and 0.51 mm ± 0.03 mm, respectively. There was no significant difference in precision between these two scanners ($p = 0.80$).

Post processing error

The error induced by the post-processing using the different software (Table 2, study 3) is shown in Table 5. The post-processing standard deviation (Table 5: 0.04 mm, 0.03 mm, and 0.06 mm for the Avanto MRI, M4D Scan, and Structure Sensor, respectively) was 10 times lower than the accuracy standard deviation (Table 3: 0.3 mm, 0.3 mm, 0.5 mm for the Avanto MRI, M4D Scan, and Structure Sensor, respectively), thus meaning that post-processing has a limited effect on the accuracy analysis.

Discussion

In craniomaxillofacial surgery, 3D shape analysis has been extensively used to assess surgical outcomes objectively [2,5-10,22,29]. In this study, the accuracy, precision, and usability of various 3D scanners to capture the face shape was assessed. The 3dMDface System was chosen to be the gold standard against which other scanners were compared, as previous studies have shown accuracy of this system to be within 1 mm when compared with conventional anthropometric measurements [28]. It should be noted that, in this study, the Avanto MRI and the M4D Scan have demonstrated similar levels of accuracy compared to anthropometric measurements by Wong et al. (2008) [28], in both studies relative to the 3dMDface System. It must be noted that the high cost of MRI may prevent routine surface scanning, contrary to the other three more affordable surface scanners.

RMS was computed as a measure of overall accuracy, relative to the 3dMDface System. RMS was found to be lowest for the M4D Scan and significantly better than the Avanto MRI and Structure Sensor. Clinically, deviations larger than 2 mm are considered unreliable [26]. All systems showed large percentages of data points within the reliable range: 85%, 94%, and 80% for the Avanto MRI, M4D Scan, and Structure Sensor, respectively. However, the usefulness of assessing overall shape correspondence with a single measure, i.e. RMS, can be limited when local areas are of interest, or areas with high curvatures. In this case, colourmaps may be more useful since they display local deviations. Additionally, accuracy is of paramount importance for landmark based analysis [30]. Thus, the clinical usability of some 3D scanners may be limited due to a lack of local accuracy, even when overall RMS is satisfactory.

Precision for the M4D Scan and Structure Sensor, expressed in RMS, were found to be 0.50 mm for both systems. It has to be noted that even though with high precision, accuracy is not granted. The accuracy of the M4D Scan was 0.71 mm, and of the Structure Sensor was 1.33 mm. This implies that even though the Structure Sensor was as precise as the M4D scan, it was less accurate. In other words, it was consistently relatively less accurate. This is supported by the colourmaps, which revealed relative large deviations in areas with high curvatures. The large mesh size generated by the structure scanner and software does not accurately define high curvature areas such as the nose, but is effective when describing less complex areas such as head shape, cheek and chin contour. Furthermore, it was shown that the post-processing steps do not induce errors that interfere with the accuracy analysis.

Factors that influence scan quality are lighting, scanner alignment and placement, facial expression of the subject, adequate coverage of hair, the examiner, and software post-processing [12,30]. A limitation of this study is the use of different head positions. A supine position in the MRI scanner, in contrast to a neutral head position, introduces some deviations as seen in the jaw and cheeks in the colourmaps. These differences are likely to be due to the effects of gravity on deformable soft tissues of the face and reflect the fact that facial form is different in the supine and upright position.

In addition to the parameters above, important clinical considerations have to be made, in particular for paediatric patients [13]. An advantage of the 3dMDface System is its low acquisition time of 1.5 ms, thereby minimising motion artefacts and reducing the need of patient compliance [28]. However, hand-held systems bear the advantage that they can be used in wards, operating theatres, and in outpatient clinics, contrary to 3dMDface System and other static systems. It must be noted that the amount of volunteers in this cohort is limited and that all volunteers were adults with no craniofacial abnormalities.

Even though the Structure Sensor presented the lowest accuracy, the main advantages of this system are the user-friendly interface and portability of the iPad. It comes with an open source software development kit, which allows for custom-made software. Therefore, multiple software applications are available, each with their own advantages and disadvantages. We used Occipital's own software, but future customised software, purposely built for craniomaxillofacial applications, may give better results. Furthermore, the use of infrared LED is advantageous compared to white light LED as in the M4D Scan, because it does not disturb the patient. Based on our findings it is foreseeable that all-in-one hand-held systems may play a more prominent role in future craniomaxillofacial 3D scanning, especially with combined powerful hardware and simple, yet powerful software.

There are numerous 3D scanners on the market, many more than those presented in this study. The surface scanners used in this study represent those available in our centre, but as discussed above, they also represent scanners of various cost, portability, and quality. Among others, companies that produce 3D scanners include 3dMD, Axisthree (Belfast, Ireland), Canfield Scientific (Fairfield, NJ, USA), Crisalix 3D (Bern, Switserland), and Di3D (Glasgow, UK). A review of high-end static scanning systems can be found in literature [15]. Furthermore, a recent study with 41 volunteers on the accuracy of Artec EVA (Artec Group, Luxembourg) and FaceScan3D (3D-Shape, Erlangen, Germany), found mean errors of a phantom between 0.228 - 0.241 mm and 0.523 - 0.630 mm for the handheld and static system respectively [33].The findings presented in this study may also apply to other areas of plastic and reconstructive surgery, for example breast and hand surgery, and cleft lip and palate [14,20,33,34].

Conclusion

The accuracy and precision of four 3D scanners was assessed for craniomaxillofacial imaging. Surface maps were employed as a powerful tool to represent distance deviations between scanners. Precision error of the M4D Scan and Structure sensor, and precision error of the post-processing protocol were found to be more than 10 times lower than accuracy errors. In comparison to the 3dMDface System, 86%, 94%, and 80% of data points of the Avanto MRI, M4D Scan, and Structure Sensor, respectively, were within a clinically acceptable range of 2 mm. The M4D Scan showed significantly best RMS, better than the Avanto MRI and Structure Sensor. For Avanto MRI, deviations occurred from a different head position (supine vs. neutral), suboptimal slice thickness, and the inability to capture facial hair. The Structure Sensor lacks hardware and software to accurately characterise areas with complex shape and high curvature, but is good at describing general facial form. Nonetheless, it still shows fair agreement with systems more than tenfold its cost and portability, and direct visualisation show great promise for clinical use. Appropriate balance between technical requirements and clinical needs will drive the use of different scanners for each specific application.

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Conflict of interest

None.

References

1) Farkas LG. Accuracy of anthropometric measurements: past, present, and future. *Cleft Palate Craniofac J*. 1996;33(1):10-8.
2) Honrado CP, Larrabee WF Jr. Update in three-dimensional imaging in facial plastic surgery. *Curr Opin Otolaryngol Head Neck Surg*. 2004;12(4):327-31.
3) Lekakis G, Claes P, Hamilton GS 3rd, Hellings PW. Three-Dimensional Surface Imaging and the Continuous Evolution of Preoperative and Postoperative Assessment in Rhinoplasty. *Facial Plast Surg*. 2016;32(1):88-94. Doi: 10.1055/s-0035-1570122.
4) Edler R, Rahim MA, Wertheim D, Greenhill D. The use of facial anthropometrics in aesthetic assessment. *Cleft Palate Craniofac J*. 2010;47(1):48-57.
5) Da Silveira AC, Daw JL Jr, Kusnoto B, Evans C, Cohen M. Craniofacial applications of three-dimensional laser surface scanning. *J Craniofac Surg*. 2003;14(4):449-56.
6) Hammond P. The use of 3D face shape modelling in dysmorphology. *Arch Dis Child*. 2007;92(12): 1120-26.
7) Krimmel M, Schuck N, Bacher M, Reinert S. Facial surface changes after cleft alveolar bone grafting. *J Oral Maxillofac Surg*. 2011 Jan;69(1):80-3.
8) van Loon B, Maal TJ, Plooij JM, et al. 3D Stereophotogrammetric assessment of pre- and postoperative volumetric changes in the cleft lip and palate nose. *Int J Oral Maxillofac Surg*. 2010;39(6):534-40.
9) van Loon B, van Heerbeek N, Bierenbroodspot F, et al.Three-dimensional changes in nose and upper lip volume after orthognathic surgery. *Int J Oral Maxillofac Surg*. 2015;44(1):83-9.
10) Tenhagen M, Bruse JL, Rodriguez-Florez N, Angullia F, Borghi A, Koudstaal M, Schievano S, Jeelani O, Dunaway D. 3D-handheld scanning to quantify head shape changes in spring assisted surgery for sagittal craniosynostosis. *J Craniofac Surg*. 2016;27(8):2117-2123.
11) Giovanoli P, Tzou CH, Ploner M, Frey M. Three-dimensional video-analysis of facial movements in healthy volunteers. *Br J Plast Surg*. 2003;56(7):644-52.
12) Heike CL, Cunningham ML, Hing AV, Stuhaug E, Starr JR. Picture perfect? Reliability of craniofacial anthropometry using three-dimensional digital stereophotogrammetry. *Plast Reconstr Surg*. 2009;124(4):1261-72.
13) Heike CL, Upson K, Stuhaug E, Weinberg SM. 3D digital stereophotogrammetry: a practical guide to facial image acquisition. *Head Face Med*. 2010;6:18. doi: 10.1186/1746-160X-6-18.
14) Lee S. Three-dimensional photography and its application to facial plastic surgery. *Arch Facial Plast Surg.* 2004;6(6):410-4.
15) Tzou CH, Artner NM, Pona I, et al. Comparison of three-dimensional surface-imaging systems. *J Plast Reconstr Aesthet Surg*. 2014;67(4):489-97
16) Structure Sensor – Capture the world in 3D. 2016. Occipital, Inc. http://structure.io/ [accessed 6 July 2016]
17) 3dMDface System. 2016. 3dMD. http://www.3dmd.com/3dmd-systems/#face [accessed 17 June 2016]
18) Comparison: M4D Scan or Structure Sensor. 2003-2009. Rodin4D. http://rodin4d.com/en/Products/acquisition/comparison-m4d-scan-vs-structure-sensor [accessed 17 June 2016]
19) Geng ZJ. Rainbow three-dimensional camera: new concept of high-speed three-dimensional vision systems. *Opt. Eng.* 1996;35(2):376-83.
20) Burke PH, Banks P, Beard LF, Tee JE, Hughes C. Stereophotographic measurement of change in facial soft tissue morphology following surgery. *Br J Oral Surg*. 1983;21(4):237-45.
21) Papadopoulos MA, Christou PK, Christou PK, et al. Three-dimensional craniofacial reconstruction imaging. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2002;93(4):382-93.

22) Staal FC, Ponniah AJ, Angullia F, Ruff C, Koudstaal MJ, Dunaway D. Describing Crouzon and Pfeiffer syndrome based on principal component analysis. *J Craniomaxillofac Surg*. 2015;43(4):528-36.

23) von Elm E, Altman DG, Egger M, Pocock SJ, Pocock SJ, Gøtzsche PC, Vandenbroucke JP; STROBE Initiative. The strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. *Lancelet* 2007;370(9596):1453-7
24) Antiga L, Piccinelli M, Botti L, Ene-Iordache B, Remuzzi A, Steinman DA. An image-based modelling framework for patient-specific computational hemodynamics. *Med Biol Eng Comput*. 2008;46:1097-112.
25) Ahrens J, Geveci B, Law C. ParaView: An end-user tool for large data visualization. In: Hansen C, Johnson C, *The Visualization Handbook*, Elsevier, Amsterdam. 2005.
26) Aung SC, Ngim RCK, Lee ST. Evaluation of the laser scanner as a surface measuring tool and its accuracy compared with direct facial anthropometric measurements. *Brit J Plast Surg*. 1995;48(8):551-8.
27) Lübbers HT, Medinger L, Kruse A, Grätz KW, Matthews F. Precision and accuracy of the 3dMD photogrammetric system in craniomaxillofacial application. *J Craniofac Surg*. 2010;21(3):763-7.
28) Wong JY, Oh AK, Ohta E, et al. Validity and reliability of craniofacial anthropometric measurement of 3D digital photogrammetric images. *Cleft Palate Craniofac J*. 2008;45(3):232-9.
29) Ponniah AJ, Witherow H, Richards R, Evans R, Hayward R, Dunaway D. Three-dimensional image analysis of facial skeletal changes after monobloc and bipartition distraction. *Plast Reconstr Surg*. 2008;122(1):225-31.
30) Kouchi M, Mochimaru M, Bradtmiller B, Daanen H, Li P, Nacher B, Nam Y. A protocol for evaluating the accuracy of 3D body scanners. *Work 41*. 2012;41:4010-17. doi: 10.3233/WOR-2012-0064-4010
31) Kovacs L, Zimmermann A, Brockmann G, et al. Accuracy and precision of the three-dimensional assessment of the facial surface using a 3-D laser scanner. *IEEE Trans Med Imaging*. 2006;25(6):742-54.
32) Modabber A, Peters F, Kniha K, Goloborodko E, Ghassemi A, Lethaus B, Hölzle F, Möhlhenrich SC. Evaluation of the accuracy of a mobile and a stationary system for three-dimensional facial scanning. *J Craniofac Surg*. 2016 http://dx.doi.org/10.1016/j.jcms.2016.08.008
33) Patete P, Eder M, Raith S, Volf A, Kovacs L, Baroni G. Comparative assessment of 3D surface scanning systems in breast plastic and reconstructive surgery. *Surg Innov*. 2012;20(5):509-15.
34) Li G, Wei J, Wang X, et al. Three-dimensional facial anthropometry of unilateral cleft lip infants with a structured light scanning system. *J Plast Reconstr Aesthet Surg*. 2013;66(8):1109-16

Figure legends

Figure 1 Overview of 3D scanners, overview of 3D data, and detail of 3D data: Avanto MRI, 3dMDface System, M4D Scan, and Structure Sensor.

Figure 2 Graphical representation of the data processing steps: (1) overlays consisting of datasets from all four scanners, (2) cutting planes from the left and right tragus to the chin, and orthogonal to that plane, (3) cropped facial sections, and (4) patched and minimally smoothed facial sections. This figure only shows the 3dMDface System scans for clarity, yet all steps were carried out for all four scans simultaneously.

Figure 3 Facial colourmap of participant 6, representative for the cohort of participants. In grey the 3dMDface System scan is shown, which is the reference image for the other three scanner colourmaps. The range is set from -2 mm (blue) to +2 mm (red), where points outside the range are displayed in the colour closest to their value.

Figure 4 Deviation and distribution of all data points for one scan pair of participant 6: M4D Scan compared to 3dMDface System. 93% of data points were within ±1 mm, and 96% were within ±2 mm.

Figure 5 Percentage of data points within deviation ranges of the Avanto MRI, M4D Scan, and Structure Sensor relative to the 3dMDface System. Deviation ranges: 0 – 1 mm (highly reliable), 1 – 1.5 mm (reliable), 1.5 – 2 mm (moderately reliable), and >2 mm (unreliable). Mean and standard deviation for all participants (n=8) shown.

Tables

Table 1 Overview of properties of the four scanners.

	Avanto MRI	**3dMDface System [13,17,18,26]**	**M4D Scan [18]**	**Structure Sensor [18]**
Hardware	1 integrated full body MRI scanner	2 modules with 3 cameras per module; flash system; stand; computer	1 hand-held scanner with 2 cameras, 4 white light LEDs; Computer	1 module, i.e. iPad accessory, with 1 camera, 1 infrared sensor, 2 infrared LEDs; iPad
Imaging modality	Magnetic resonance	Hybrid passive/active: stereophotogrammetry/ structured light	Active: structured light (white light)	Active: structured light (infrared)
Accuracy†	1 mm slices‡	0.2 mm	0.5 mm	4 mm
Acquisition time	360 s‡	1.5 ms	~ 30 s	~ 20 s
Output files	2D DICOM, mesh	Point cloud, textured mesh	Mesh	Textured mesh
Mesh density (polygons/mm^2)	0.51 ± 0.11	1.10 ± 0.08	0.44 ± 0.01	0.13 ± 0.01
Hand-held	No	No	Yes	Yes
Cost*	>250 000 USD	>20 000 USD	>15 000 USD	1000 USD

† Manufacturers' stated accuracy, varies with object distance. M4D Scan: 0.5 mm at 40 cm stand-off distance; Structure Sensor: 4 mm at 60 cm stand-off distance.

‡ Varies with acquisition sequence and parameters (e.g. slice thickness)

* An indication, actual cost depends on configuration (modules, computer/iPad, software, accessories, etc.).

Table 2 Overview of data analysis studies and the amount of datasets used.

Study	Subject	Datasets
1	Accuracy of scanners	32 (8 participants, 4 scanners, 1 scan per scanner)
2	Precision of scanners (excluding Avanto MRI and 3dMD)	12 (1 participant, 2 scanners, 6 scans per scanner)
3	Post-processing error	4 (1 participant, 4 scanners, 1 scan per scanner)

Table 3. Accuracy of the Avanto MRI, M4D Scan, and Structure Sensor relative to the 3dMDface System. Root mean square deviation (RMS) per participant, and mean and standard deviation (SD) are shown.

Participant	**RMS (mm), relative to 3dMDface System**		
	Avanto MRI	M4D Scan	Structure Sensor
1	1.76	1.05	2.28
2	1.16	0.65	1.13
3	1.25	1.02	1.15
4	1.09	1.05	1.50
5	1.16	0.55	1.40
6	0.67	0.47	1.45
7	1.00	0.44	0.83
8	0.75	0.45	0.86
Mean ± SD	1.11 ± 0.33	0.71 ± 0.28	1.33 ± 0.46

Table 4. Precision of the M4D Scan and Structure Sensor. Root mean square distance (RMS) mean and standard deviation (SD) are shown for 10 scan pairs, all of one participant.

Scan pairs	**RMS (mm)**	
	M4D Scan	Structure Sensor

1 vs 6	0.55	0.49
2 vs 6	0.50	0.54
3 vs 6	0.51	0.53
4 vs 6	0.46	0.48
5 vs 6	0.48	0.48
1 vs 2	0.56	0.56
1 vs 3	0.49	0.50
1 vs 4	0.56	0.50
1 vs 5	0.47	0.50
1 vs 6	0.55	0.49
Mean ± SD	0.51 ± 0.04	0.51 ± 0.03

Table 5. Post-processing error for one dataset (participant 7) was analysed 5 times (i.e. steps 2 – 4), for each of the three scanners (Avanto MRI, M4D Scan, and Structure Sensor) relative to the 3dMDface System. Root mean square distance (RMS) mean and standard deviation (SD) are shown.

Post-processing repetition	**RMS (mm), relative to 3dMDface System**		
	Avanto MRI	M4D Scan	Structure Sensor
1	1.00	0.44	0.83
2	0.99	0.49	0.75
3	1.06	0.47	0.79
4	0.99	0.44	0.78
5	1.06	0.41	0.67
Mean ± SD	1.02 ± 0.04	0.45 ± 0.03	0.76 ± 0.06

Figures

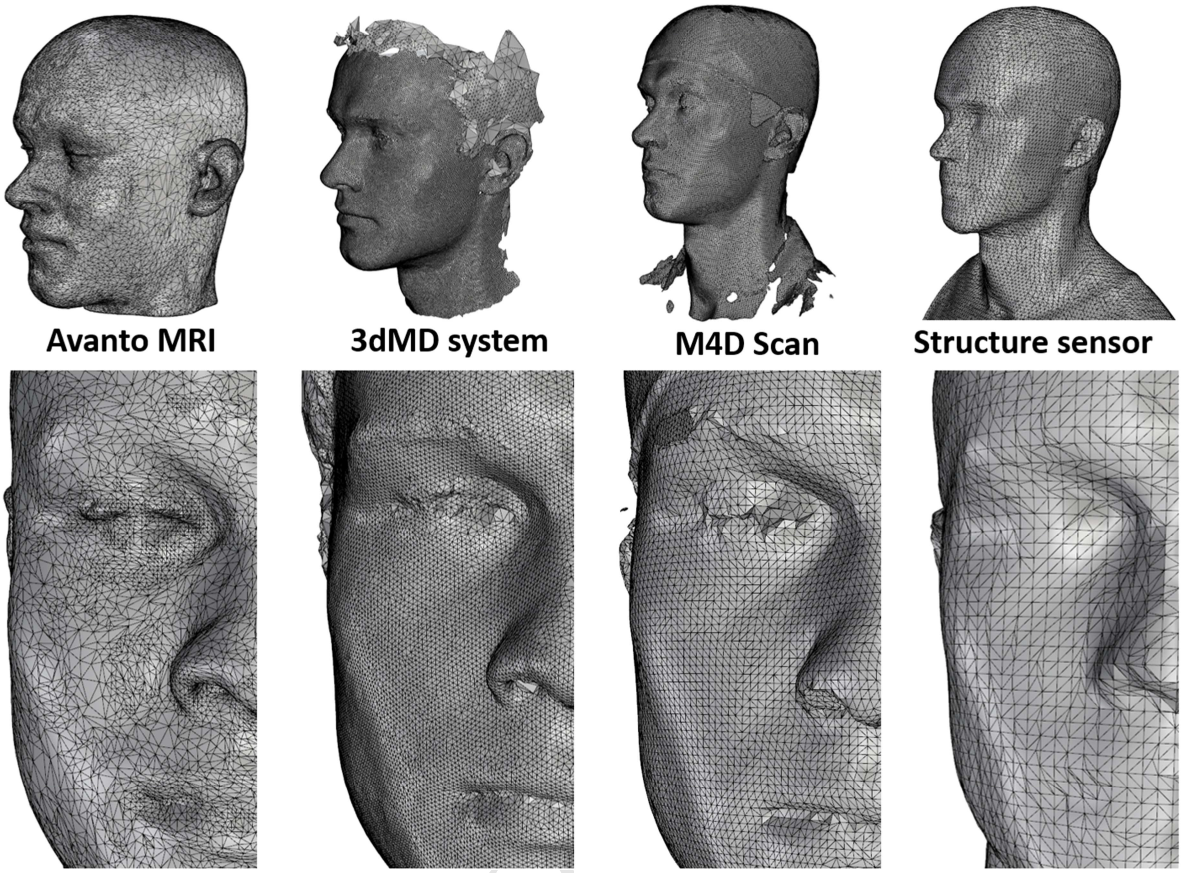

Figure 1 Overview of 3D scanners, overview of 3D data, and detail of 3D data: Avanto MRI, 3dMDface System, M4D Scan, and Structure Sensor.

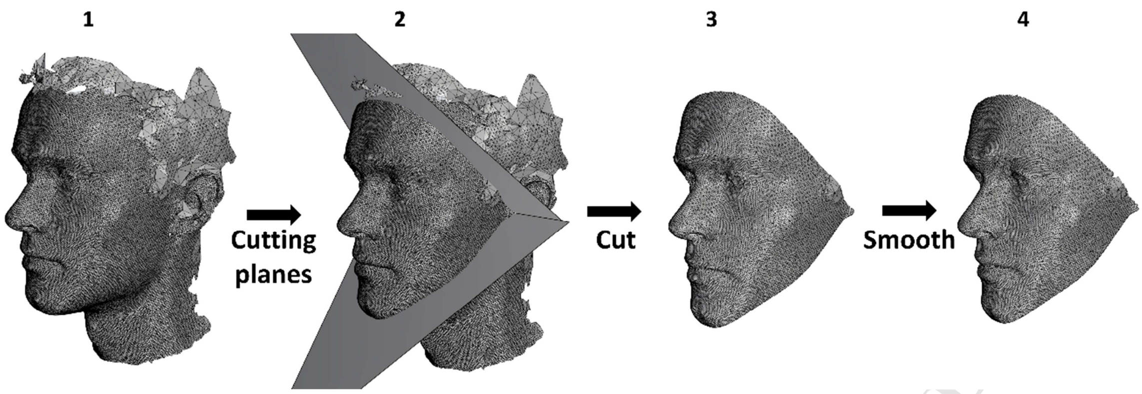

Figure 2 Graphical representation of the data processing steps: (1) overlays consisting of datasets from all four scanners, (2) cutting planes from the left and right tragus to the chin, and orthogonal to that plane, (3) cropped facial sections, and (4) patched and minimally smoothed facial sections. This figure only shows the 3dMDface System scans for clarity, yet all steps were carried out for all four scans simultaneously.

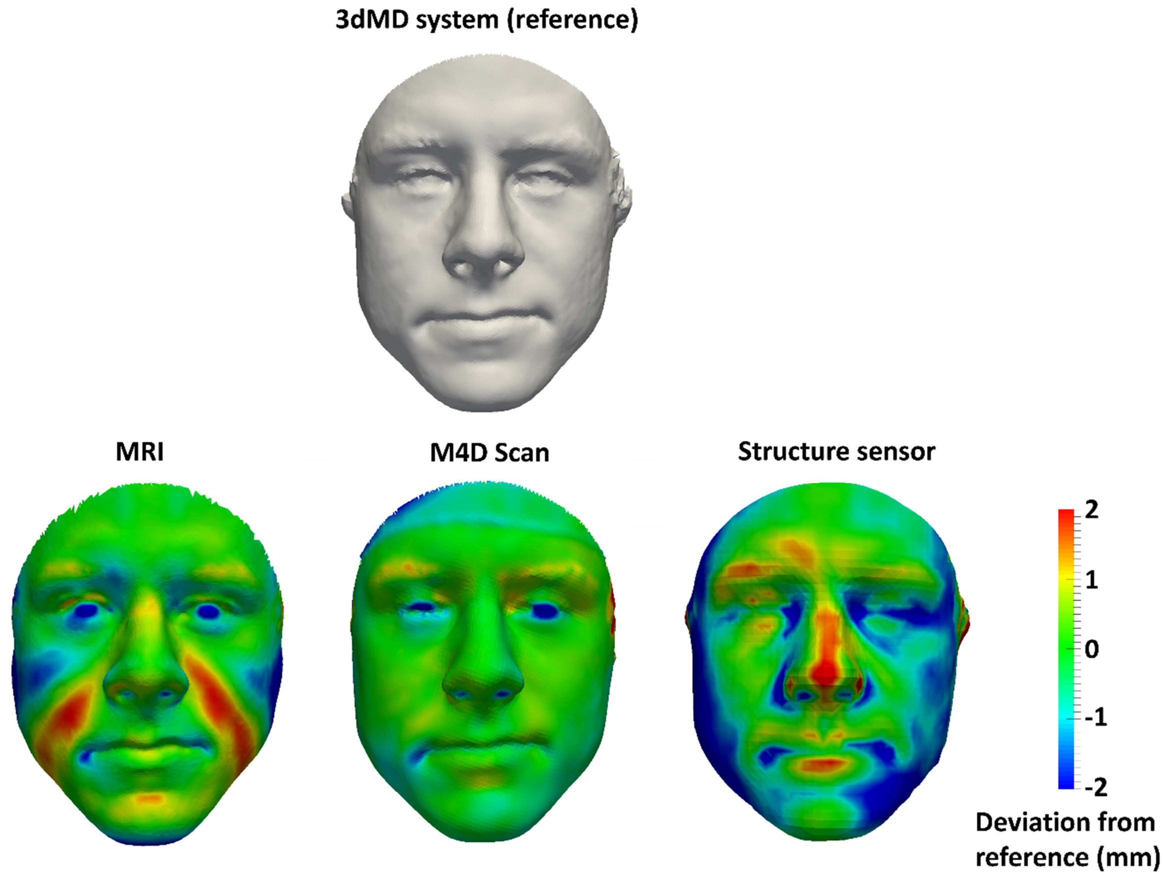

Figure 3 Facial colourmap of participant 6, representative for the cohort of participants. In grey the 3dMDface System scan is shown, which is the reference image for the other three scanner colourmaps. The range is set from -2 mm (blue) to +2 mm (red), where points outside the range are displayed in the colour closest to their value.

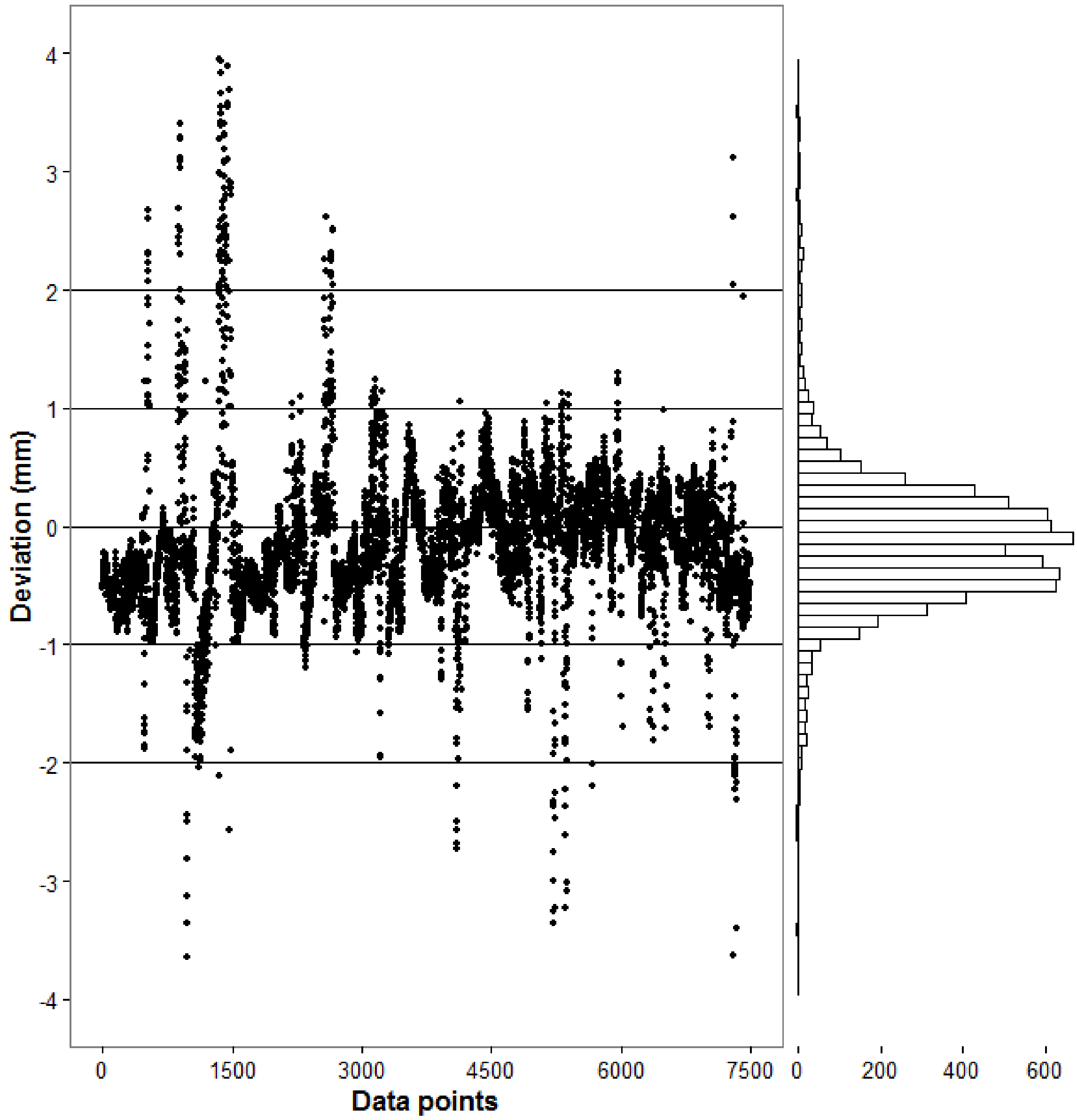

Figure 4 Deviation and distribution of all data points for one scan pair of participant 6: M4D Scan compared to 3dMDface System. 93% of data points were within ±1 mm, and 96% were within ±2 mm.

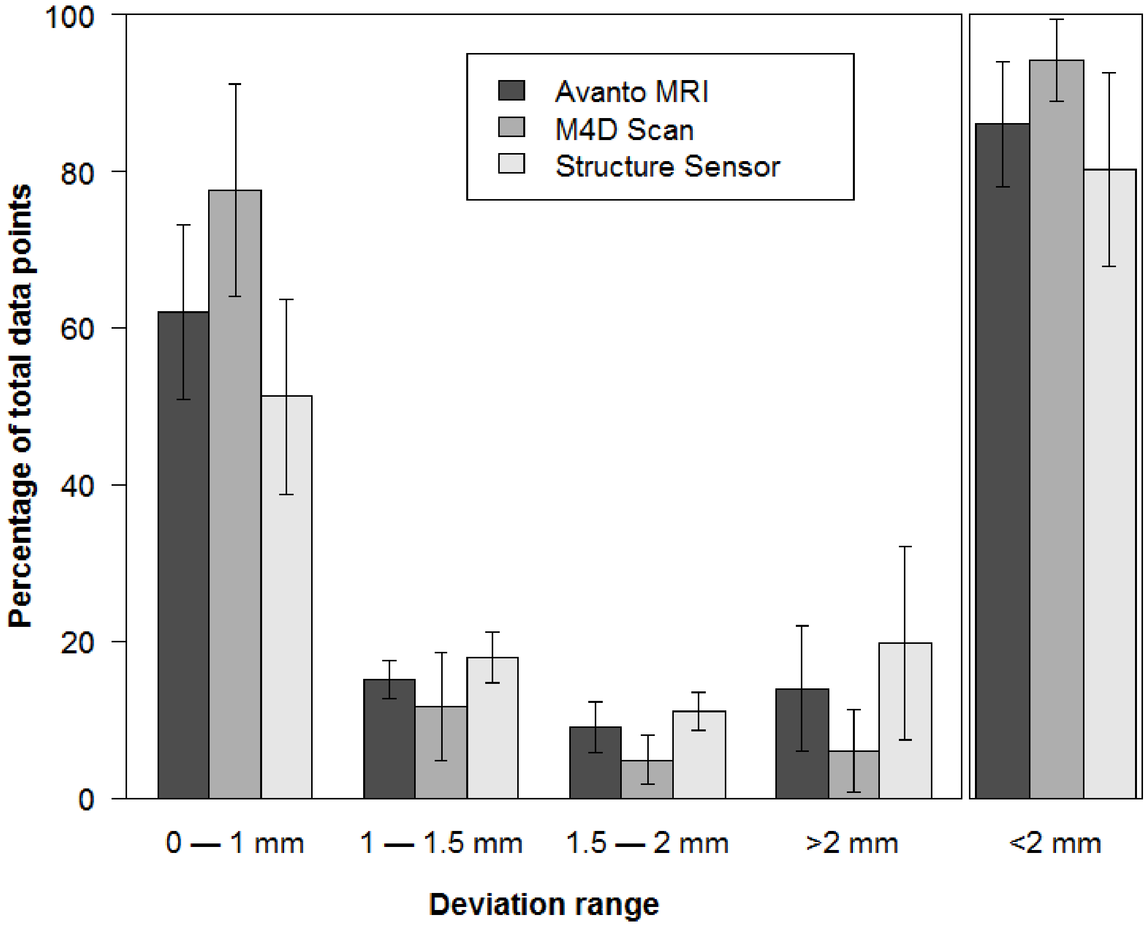

Figure 5 Percentage of data points within deviation ranges of the Avanto MRI, M4D Scan, and Structure Sensor relative to the 3dMDface System. Deviation ranges: 0 – 1 mm (highly reliable), 1 – 1.5 mm (reliable), 1.5 – 2 mm (moderately reliable), and >2 mm (unreliable). Mean and standard deviation for all participants (n=8) shown.