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Validation of a low-cost laser scanner device for the assessment of three-dimensional facial anatomy in living subjects

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Summary

The present study compared the reliability of a low-cost laser scanner device to an already-validated stereophotogrammetric instrument. Fifty volunteers underwent duplicate facial scans through laser scanner and stereophotogrammetry. Intra- and inter-instrument reproducibility of linear distances, angles, facial surface area and volume was verified through the Bland-Altman test and calculation of absolute (TEM) and relative (rTEM) technical errors of measurement; rTEM was then classified as follows: <1% excellent; 1-3.9% very good; 4-6.9% good; 7-9.9% moderate; >10% poor. The scans performed through different devices were registered and superimposed to calculate the root mean square (RMS) (point-to-point) distance between the two surfaces. The same protocol was applied to a mannequin head. In inter-instruments comparison, 12/26 measurements showed a “good” rTEM; 5 were “very good”. In intra-instrument comparison, most performances worsened, with only 10 of 26 measurements classified as “good” and “very good”. All the measurements made on mannequin scans were at least “good”, and 14/26 were “very good”. Surface area was “very good” only in intra-instrument comparison; conversely, volumes were poorly repeatable for all the comparisons. On average, RMS point-to-point distances were 0.65 mm (inter-devices comparison), 0.56 mm (mannequin scans), 0.42 mm (intra-device comparison). In conclusion, the low-cost laser scan device can be reliably applied to inanimate objects, but does not meet the standards for three-dimensional facial acquisition on living persons.

Keywords: facial anatomy, low-cost laser scanner, stereophotogrammetry, RMS (root mean square)

INTRODUCTION

Three-dimensional facial analysis represents an important field of research of human anatomy, with application in several surgical and diagnostic branches of medicine, from dentistry to maxillofacial surgery (*Farkas and Deutsch*, 1996). The introduction of modern three-dimensional (3D) image acquisition systems, such as stereophotogrammetry and laser scanning, has represented a crucial improvement, widening the type of measurements to areas, volumes and 3D-3D surface distances, and increasing the reliability of metrical assessment (*Winberg et al*., 2006; *Sawyer et al*., 2009; *Codari et al*., 2015; *Gibelli et al*., 2015; *Hong et al*., 2017). In fact, both stereophotogrammetry and laser scanners have proved to be highly reliable (*de Menezes et al*., 2010; Joe et al., 2012), and have been applied to many research fields of facial anatomy relating to surgery, anthropology and genetics (*Schwenzer-Zimmerer et al*., 2008; *Kau et al*., 2010; *Tartaglia et al*., 2012; *Sforza et al*., 2013; *Othman et al*., 2014; *Rosati et al*., 2014; *Koudelovà et al*., 2015; *Pucciarelli et al*., 2017a, 2017b).

With time, literature has validated several types of stereophotogrammetric and laser scanner devices which were found suitable for research in 3D facial anatomy (*Kau et al*., 2004; *Winberg et al*., 2006; *de Menezes et al*., 2010; *Joe et al*., 2012; *Camison et al*., 2017; *Hong et al*., 2017); however, although they reach a high reliability in assessment of different metrical measurements, they are affected by some limits, being the first of them the price. Although the technological improvement will lead to a decrease in costs in the future, the static 3D image acquisition devices still have a high price (*Fan et al*., 2017), which may not be afforded by all universities for research or by hospitals for diagnosis, treatment planning and follow-up.

Recently, novel portable stereophotogrammetric devices have been proposed on the market, with the advantage of being more economical than the static models and sharing a high reliability in assessing measurements (*Camison et al*., 2017). However, their cost remains in the order of several thousand euros, and represents the main limit for their wide diffusion in different research fields.

At the same time, other 3D image acquisition devices with an affordable price have been produced and made available on the market: an example is provided by the Sense® 3D scanner, a hand-held scanner with a spatial x/y resolution of 0.9 mm and a depth resolution of 1.0 mm at 0.5 m (*Fan et al*., 2017). It costs approximately 400 euros and can acquire the point cloud of the head in less than 1 minute (*Fan et al*., 2017).

The possible application of this type of device to facial anatomy may represent an important step for widening the chances of 3D analysis of faces in different clinical and surgical contexts. However, to our knowledge, so far the Sense® device has been applied only in one published study, in which it was used to scan the face of a cadaver for the assessment of 3D modifications due to the decomposition process (*Caplova et al.*, 2018). No study has applied this type of technology to facial analysis of living people.

In addition, the low-cost Sense® device has not been validated for the livings yet: in fact, to date, only one study has tested its reliability using a mannequin head and one patient acquired in a clinical environment (*Fan et al*., 2017). Results were reported as promising by the authors; however, no indication at all is given about the reproducibility of facial measurements on real subjects, and specifically on the possible limits due to involuntary head and facial movements.

Yet, this type of device is expected to be used more and more frequently in different areas of research, thanks to its low cost; therefore, a validation study including an adequate number of living subjects is mandatory.

The present study aims to validate a low-cost laser scanner device for the assessment of living subjects to test its application to 3D facial anatomy.

MATERIALS AND METHODS

Sample recruitment

A total of 50 adult subjects (10 men and 40 women) aged between 21 and 50 years (mean: 27.8 years; SD: 6.5 years) were recruited for the facial scan. Subjects affected by deformations and congenital and acquired pathologies affecting the face, as well as signs of recent or previous facial trauma were excluded from the study. Subjects with beards were excluded as well, as both stereophotogrammetric and laser scanner devices cannot acquire areas covered by excess facial hair.

Every participant signed an informed consent form, according to local and international ethical rules. The study followed guidelines by the Declaration of Helsinki (26.03.14; no. 92/14) and was approved by the university ethical committee (26.03.14, no. 92/14).

3D acquisition

Every participant's face was scanned through two different 3D image acquisition devices: a low-cost laser scanner (Sense®, 3DSystems, Rick Hill, SC, USA) and a static stereophotogrammetric device (Vectra-3D®: Canfield Scientific, Inc., Fairfield, NJ, USA) (Fig. 1). Every subject was scanned in neutral expression. A second Sense® facial capture was repeated after a few seconds to test the intra-device repeatability.

Capture modalities vary according to the type of device. For the stereophotogrammetric one, 50 landmarks were marked on every participant's face through a black eyeliner according to a standardized procedure for 3D acquisition (de Menezes et al., 2010). The volunteers had to keep a neutral position while sitting on a stool in front of the instrument; its three cameras acquired the facial surface simultaneously from three different points of view in 3.5 milliseconds (https://www.canfieldsci.com/imaging-systems/vectra-m3-3d-imaging-system/). On the other hand, the Sense® device had to be moved by the operator around the subject while performing a continuous acquisition of the facial surface through its laser ray and camera. The scan lasts a few seconds, and the subject had to keep the neutral position for all the acquisition time. To standardize the procedure, the acquisition time was set at 10 seconds, sufficient to perform a complete scan of the entire facial surface. Sense® acquisition does not require previous eyeliner marking, as the scan is obtained without a texture.

The entire procedure was applied also to a mannequin head, which was scanned three times through Vectra® and five times through Sense® devices to compare the performances of both devices in cases of inanimate objects.

In addition, a box covered by graph paper was scanned with both Vectra® and Sense® acquisition systems to test accuracy and repeatability of linear distances, surface areas and volumes. Ten measurements were performed for each type and compared with the real values through calculation of absolute and relative technical errors of measurement (TEM/rTEM).

Data elaboration

The 3D scans obtained through both devices were elaborated through VAM® software (Vectra Analysis Module, Canfield Scientific, Inc., Fairfield, NJ, USA).

At first, 14 linear and 12 angular measurements were automatically calculated through Faces software, specifically developed for the automatic extraction of these measurements from 3D coordinates (Table 1, Fig. 2). This step requires that 17 facial landmarks be identified on the 3D scans (*Pucciarelli et al*., 2017a). For the stereophotogrammetric facial models, landmarks were located according to the eyeliner marks; for the Sense® scans, landmarks were located with the only the help of the geometrical characteristics of the 3D surface.

In a second step, a facial area of interest (FAI) was selected in each 3D facial model as the area included between the trichion, frontotemporale, zygion, tragion, gonion and gnathion landmarks; these points were manually placed and the FAI was automatically selected through VAM® software (*Gibelli et al.*, 2017a, 2017b). Surface area and volume of the FAI were obtained.

Finally, FAIs acquired through stereophotogrammetry and laser scanner were superimposed on each other to reach the least mean point-to-point distance between the entire 3D surfaces. This procedure was automatically performed by VAM® software. Once the superimposition was performed, RMS point-to-point distances between the two 3D scans were automatically calculated (Fig. 3).

Statistical analysis

Two types of comparison were performed, respectively between the stereophotogrammetric and laser scanner models and between the two scans from the laser scanner.

Concordance of linear and angular measurements, facial surface area and volume of FAIs were assessed through a Bland-Altman test (Giavarina, 2015). In addition, the absolute and relative technical errors of measurement (TEM/rTEM) were calculated (*Adao Perini et al*., 2005), and evaluated according to five categories: <1% excellent; 1-3.9% very good; 4-6.9% good; 7-9.9% moderate; >10% poor (19).

RESULTS

Overall results for linear and angular measurements are reported in Tables 2-4.

For inter-instruments comparisons, 17 of 26 measurements achieved a "very good" or a "good" performance, with agreement ranging between 61.1% and 92.0% (TEM between 2.2 mm and 8.0 mm for linear distances, and between 1.8° and 6.8° for angles).

The measurements performing the worst were forehead length (tr-n), mandibular ramus length (t_m-go_m), nasal convexity (sn-n-prn), and both angles of eye fissure (ex-en vs TH), all classified as "poor" rTEM values. In addition, "moderate" rTEM values were shown by four measurements involving the lower third of face: lower facial height (sn-pg), mouth width (ch_r-ch_l), mandibular body length (pg-go_m), and facial divergence [(t_m-n) vs (go_m-pg)]. No case of "excellent" rTEM was recorded.

When repeated scans of the same person obtained through Sense® device were compared, in general the performances of most of measurements worsened: only 10 measurements among linear distances and angles were classified as "very good" or "good", with a repeatability ranging between 69.1% and 91.6% (TEM between 2.9 mm and 5.5 mm for linear distances, and between 2.0° and 5.7° for angles). The rest of the measurements were classified as "moderate" or "poor", being those performing worst with regard to lower facial height (sn-pg), mandibular ramus length (t_m-go_m), both angles of eye fissure (ex-en vs TH), upper facial convexity (t_r-n-t_l), middle facial convexity (t_r-prn-t_l), lower facial convexity (t_r-pg-t_l), nasal convexity (sn-n-prn), and facial divergence [(t_m-n) vs (go_m-pg)]. In 16 of 26 cases, the performances were lower than those obtained with Vectra®-Sense®.

On the other hand, the comparison between Vectra® and Sense® 3D models of the mannequin reached the highest performance, with 24 of 26 rTEMs classified as “very good” and “good” and two as “excellent”. In this case, concordance ranged between 63.2% and 98.5%, whereas TEM was between 0.7 and 7.5 mm for linear distances, and between 0.6° and 4.8° for angles.

Repeatability of FAI surface area was “poor” for Vectra®-Sense® and “very good” for Sense®-Sense® comparisons: Vectra®-Sense® comparison of mannequin facial models was classified as “moderate”. rTEM values for FAI volume were “poor” for all the comparisons (Table 5).

With regard to 3D-3D registration procedures, in the case of living subjects, the mean RMS distance was 0.65 mm (SD: 0.12) for Vectra®-Sense® comparison, and 0.42 mm (SD: 0.17) for Sense®-Sense® comparison; for the mannequin head, the same value between Vectra® and Sense® models was 0.56 mm (SD: 0.02 mm).

With respect to measurements on the experimental model covered by graph paper, the Vectra® system gave excellent results in regard to linear distances (TEM: 0.3 mm; rTEM: 0.9%) and very good in the case of surface areas (TEM: 0.2 cm^2; rTEM: 1.1%) and volumes (TEM: 0.8 cm^3; TEM: 2.9%). The same values were worse for measurements performed on the Sense® 3D model, although linear distances and surface areas were still acceptable, being classified respectively as “very good” (TEM: 0.6 mm; rTEM: 1.6%) and “good” (TEM: 0.5 cm^2; rTEM: 3.1%). On the other side, volumes gave a “poor” repeatability (TEM: 3.4 cm^3; rTEM: 13.8%).

DISCUSSION

Three-dimensional image acquisition systems are gaining a growing importance in several fields of research: this phenomenon has already been acknowledged in the literature, as several authors have tested the reliability of stereophotogrammetric and laser scanner devices in facial anatomy (*Kau et al*., 2004; *Winberg et al*., 2006; *de Menezes et al*., 2010; *Joe et al*., 2012; *Hong et al*., 2017; *Camison et al*., 2017).

The introduction of low-cost devices may represent a push towards more diffuse application of 3D image acquisition technologies, especially in contexts in which the high costs of the fixed and already validated devices cannot be afforded. For this reason, the validation of these instruments, often designed for different purposes, is a crucial task in the actual field of facial anatomy.

The present study was designed to test the performances of Sense® laser scanner in all the declination of facial assessment, including not only linear and angular measurements, but also surfaces and volumes, which are acquiring a growing importance in research and clinics (*Sforza et al*., 2014a, 2014b; *Gibelli et al*., 2015; *Ozer et al*., 2016). In addition, 3D-3D point-to-point distances, calculated after registration of 3D models, were also tested, as they have had several applications in the literature (*Camison et al*., 2017; *Gibelli et al*., 2017a, 2017b; *Pucciarelli et al*., 2018).

The inter-instrument comparison verified that only 17 of 26 linear and angular measurements showed an acceptable repeatability between Vectra® and Sense® scans; as a reference, we can consider the same values recorded in the Vectra® intra-device comparison, in which 17 of 26 measurements were classified as “excellent”, 7 of 26 as “very good” and 2 as “good” (*Gibelli et al*., 2018). The performances worsened in the Sense®-Sense® intra-device comparison, in which only 10 of 26 measurements could be classified as at least “good”.

The results can be adequately justified only considering the different measurement protocol of the two devices: while the stereophotogrammetric device performs three simultaneous captures of 3.5 milliseconds, the laser scanner performs a unique capture lasting several seconds. During both acquisitions, the subject must stay still. However, involuntary head and facial movements cannot be fully controlled, and they increase with acquisition time; therefore, the longer the scan, the greater the muscular contractions modifying the final 3D facial model. Indeed, the measurements with low repeatability concerned mainly the oral and orbital area, where involuntary movements are reported to be most evident (*de Menezes et al*., 2010). Clearly the performances are expected to change modifying the acquisition time of Sense® device: for example, decreasing the capture time could lead to a lower influence of facial mobility. In the present study, a conventional time of 10 seconds was arbitrarily chosen for each capture, as it was the adequate time for a complete facial acquisition; however, further studies at different acquisition times are needed to determine which is the best capture time for this type of device.

Another relevant difference that may have had an impact on the present results concerns texture. The Vectra® device reproduces a texture model, which obviously helps in detecting landmarks that have been previously marked on the face (*de Menezes et al*., 2010). On the other hand, the Sense® device does not provide texture information; therefore, facial landmarks must be identified on the face with the help of only the 3D surface (Fig. 1) (*Marmulla et al*., 2003; *Kovacs et al*., 2006). In the present study, landmarks had already been marked on the skin prior to digitization through Vectra® device: in fact, labeling landmarks prior to acquisition improves the precision of the subsequent measurement procedures (*Weinberg et al*., 2004). Differences in position between previously marked landmarks and the same reference points detected merely on the 3D surface may explain the error encountered in inter-device comparison. In addition, the same variables are expected to increase in intra-device comparison, as both 3D scans suffer the same limitations in landmark detection, with consequent increase in TEM and rTEM values and reduction of repeatability. Moreover, differences in locating facial landmarks may explain the low performance of facial area and volume in Vectra®-Sense® comparisons, as they affect the definition of FAI as well. As reference, Vectra® intradevice rTEM for facial area and volume were respectively 0.8% and 2.2% (30).

On the other hand, the repeatability of most of measurements increased passing from living people to inanimate mannequins, where the influence of head and facial movements is excluded; in this case, no measurement reached a rTEM classification lower than “good”, with TEMs up to 5.6 mm for linear distances and 6.3° for angles. These results suggest that the best scenario for using Sense® is one involving either inanimate objects or deceased persons, as already proposed by the scanty literature so far available on this device (*Fan et al*., 2017; *Caplova et al*., 2018).

With regard to RMS point-to-point distance, the smallest value was shown by Sense®-Sense® comparison, with 0.42 mm, whereas it was higher in the Vectra®-Sense® comparison (0.65 mm). The mannequin Vectra®-Sense® comparison yielded intermediate values (0.56 mm). In a recent investigation comparing static and portable stereophotogrammetric instruments, Camison et al. found a mean RMS of 0.43 mm (*Camison et al*., 2017). The present results seem to suggest that Sense® provides valid scans to perform 3D-3D registration and calculation of RMS point-to-point distances; however, caution should be taken when the superimposed models come from different devices because of the obvious differences in acquisition procedures.

One limitation of the present investigation is the location of data collection: all procedures were made in a research laboratory. Other locations, both indoor and outdoor, may have increased environmental noise, with a possible increment in involuntary movements. Another limitation is sample composition: we measured only cooperative adult subjects, who were expected to maintain the requested head and face positions with limited involuntary movements. Therefore, results may change in young and/or uncooperative persons (*Kau et al*., 2004; *Pucciarelli et al*., 2017a, 2017b).

CONCLUSION

In conclusion, the present article first validated the use of the low-cost Sense® laser scanner in the field of 3D facial imaging. Results suggest that the device does not meet the standards for 3D facial acquisition according to the specific needs and standards of cephalometry. On the other hand, it provides a reliable acquisition of facial surface for the assessment of linear and angular measurements in the case of inanimate objects or subjects. This characteristic justifies its application to the acquisition of faces from cadavers, as already done (*Caplova et al*., 2018), as it is portable and does not require space, whereas the static stereophotogrammetric instrument must be used in a fixed location with a dedicated set. Another practical advantage is represented by the cost, as the laser scan cost is about 1.4% of that of the stereophotogrammetric device.

These indications may provide an important first step for improving awareness among researchers of the advantages and disadvantages of different 3D image acquisition devices and cautions towards their incorrect use.

In conclusion, the present article first validated the use of the low-cost Sense® laser scanner

in the field of 3D facial imaging. Results suggest that the device does not meet the standards for 3D facial acquisition in living persons according to specific needs

Conflict of interest

The authors declare that they have no conflict of interest.

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Fig. 1. Example of a facial scan through stereophotogrammetric Vectra-3D (a) and laser scanner Sense® devices (b).

Fig. 2. Detail of 17 facial landmarks used for the automatic calculation of distances and angles (z); tr: trichion; n: nasion; prn: pronasale; sn: subnasale; pg: pogonion; ex: exocanthion; en: endocanthion; ch: cheilion; t: tragus; zy: zygion; go: gonion

Fig. 3. Phases of registration and superimposition of two 3D models. (a) Facial area of interest (FAI) from stereophotogrammetric Vectra-3D device; (b) FAI from Sense® device; (c) registration of two FAIs according to the least point-to-point distance between the two models; (d) measurement of point-to-point distance between the two 3D models, represented through different color degrees.

Linear distances		Angular measurements	
Abbreviation	Definition	Abbreviation	Definition
tr-n	Forehead length	ex_r-ex_r vs TH	Right inclination of the eye fissure versus the true horizontal plane
n-pg	Total facial height	ex_l-ex_l vs TH	Left inclination of the eye fissure versus the true horizontal plane
n-sn	Nasal height		
sn-pg	Lower facial height		
ex_r-ex_l	Intercanthal distance	t_r-n-t_l	Upper facial convexity
zy_r-zy_l	Facial width	t_r-prn-t_l	Middle facial convexity
t_r-t_l	Middle facial width	t_r-pg-t_l	Lower facial convexity
ch_r-ch_l	Mouth width	go_r-pg-go_l	Mandibular convexity
go_r-go_l	Lower facial width		
t_m-n	Upper facial depth	n-sn-pg	Facial convexity (excluding nose)
t_m-sn	Midfacial depth	n-prn-pg	Facial convexity (including nose)
t_m-pg	Lower facial depth	sn-n-prn	Nasal convexity
pg-go_m	Mandibular body length	t_r-go_r-pg	Right gonial angle
t_m-go_m	Mandibular ramus length	t_l-go_l-pg	Left gonial angle
		(t_m-n) vs (go_m-pg)	Facial divergence (midfacial to mandibular plane angle)

Table 1. Abbreviations and definitions for the analysed linear and angular measurements.

<<TABLE 1 FOOTNOTE>>r = right, l = left, m = mid-landmark; TH = true horizontal plane.

		Abbreviation	Vectra-Sense	Sense-Sense	Vectra-Sense (mannequin)
Linear distances	Vertical distances	tr-n	28.8	57.7	71.1
		n-pg	79.8	79.6	90.8
		n-sn	77.4	65.9	87.7
		sn-pg	62.9	58.3	73.5
		t_m-go_m	38.4	14.7	92.6
	Horizontal distances	ex_r-ex_l	77.8	84.1	96.1
		zy_r-zy_l	88.6	57.8	94.0
		t_r-t_l	90.0	88.0	98.5
		ch_r-ch_l	59.5	55.6	80.7
		go_r-go_l	61.1	79.4	94.9
	Sagittal distances	t_m-n	71.8	69.1	87.0
		t_m-sn	68.7	63.9	94.8
		t_m-pg	72.0	55.6	92.3
		pg-go_m	56.6	60.9	72.9
Angles	Frontal plane	ex_r-ex_r vs TH	-53.1	-19.8	75.9
		ex_l-ex_l vs TH	-29.2	-14.8	84.1
	Horizontal plane	t_r-n-t_l	74.3	46.2	89.7
		t_r-prn-t_l	76.9	46.6	95.6
		t_r-pg-t_l	69.0	47.4	92.2
		go_r-pg-go_l	64.1	77.3	65.5
	Sagittal plane	n-sn-pg	86.1	89.6	93.6
		n-prn-pg	92.0	91.6	96.3
		sn-n-prn	47.2	31.7	78.5
		t_r-go_r-pg	74.7	73.7	83.2
		t_l-go_l-pg	68.6	78.4	79.1
		(t_m-n) vs (go_m-pg)	53.0	30.8	63.2

Table 2. Repeatability according to Bland-Altman test for linear distances and angles.

<<TABLE 2 FOOTNOTE>>All values are expressed as percentages (%). r = right, l = left, m = mid-landmark; TH = true horizontal plane.

		Abbreviation	Vectra-Sense	Sense-Sense	Vectra-Sense (mannequin)
Linear distances (mm)	Vertical distances	tr-n	9.6	6.6	3.5
		n-pg	4.1	4.0	3.3
		n-sn	2.2	4.2	1.3
		sn-pg	4.4	5.9	3.0
		t_m-go_m	5.4	7.9	0.7
	Horizontal distances	ex_r-ex_l	3.9	2.9	3.8
		zy_r-zy_l	2.8	10.0	7.5
		t_r-t_l	2.6	3.0	6.0
		ch_r-ch_l	3.6	4.6	2.9
		go_r-go_l	8.0	4.2	2.3
	Sagittal distances	t_m-n	5.8	5.5	4.0
		t_m-sn	5.5	6.6	2.7
		t_m-pg	5.5	9.1	2.7
		pg-go_m	6.5	6.0	3.2
Angles (°)	Frontal plane	ex_r-ex_r vs TH	3.6	3.1	0.6
		ex_l-ex_l vs TH	3.2	3.8	1.1
	Horizontal plane	t_r-n-t_l	4.3	8.2	1.3
		t_r-prn-t_l	3.4	7.3	1.4
		t_r-pg-t_l	3.6	6.7	1.7
		go_r-pg-go_l	5.1	4.1	4.8
	Sagittal plane	n-sn-pg	5.0	4.0	1.5
		n-prn-pg	1.8	2.0	0.7
		sn-n-prn	2.6	2.5	0.9
		t_r-go_r-pg	5.4	5.7	3.5
		t_l-go_l-pg	6.8	4.6	4.1
		(t_m-n) vs (go_m-pg)	3.8	5.8	2.2

Table 3. TEM value for linear distances and angles.

<<TABLE 3 FOOTNOTE>>All values are expressed as percentages (%). r = right, l = left, m = mid-landmark; TH = true horizontal plane.

		Abbreviation	Vectra-Sense	Sense-Sense	Vectra-Sense (mannequin)
Linear distances	Vertical distances	tr-n	13.9	9.5	4.3
		n-pg	3.8	3.7	3.1
		n-sn	4.2	7.6	2.5
		sn-pg	8.0	10.8	5.6
		t_m-go_m	10.7	14.8	1.3
	Horizontal distances	ex_r-ex_l	4.3	3.2	3.9
		zy_r-zy_l	2.8	7.4	5.6
		t_r-t_l	1.9	2.1	5.0
		ch_r-ch_l	7.3	9.6	5.1
		go_r-go_l	6.7	3.6	1.9
	Sagittal distances	t_m-n	6.6	6.3	5.0
		t_m-sn	6.0	7.2	2.9
		t_m-pg	5.1	8.3	2.3
		pg-go_m	8.5	7.8	3.9
Angles	Frontal plane	ex_r-ex_r vs TH	25.1	22.7	4.3
		ex_l-ex_l vs TH	22.2	26.3	6.0
	Horizontal plane	t_r-n-t_l	5.6	10.6	1.5
		t_r-prn-t_l	5.1	10.7	2.1
		t_r-pg-t_l	5.4	10.4	2.8
		go_r-pg-go_l	6.8	5.5	6.3
	Sagittal plane	n-sn-pg	3.1	2.5	0.9
		n-prn-pg	1.4	1.6	0.5
		sn-n-prn	12.1	12.3	4.2
		t_r-go_r-pg	4.4	4.8	2.9
		t_l-go_l-pg	5.6	3.8	3.6
		(t_m-n) vs (go_m-pg)	8.9	13.8	5.8

Table 4. rTEM value for linear distances and angles.

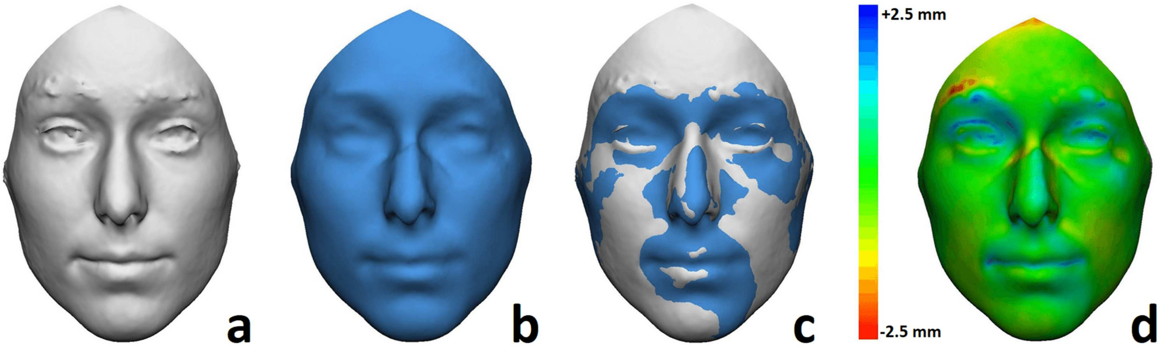
<<TABLE 4 FOOTNOTE>>All values are expressed as percentages (%). r = right, l = left, m = mid-landmark; TH = true horizontal plane; rTEM = relative technical error of measurement. In

white cells excellent, in light gray very good, in intermediate gray good, in dark gray moderate, and in black poor rTEM values.

		Vectra-Sense	Sense-Sense	Vectra-Sense (mannequin)
Surface areas	BA (%)	12.8	79.1	85.3
	TEM (cm^2)	50.9	11.9	26.6
	rTEM (%)	15.4	3.6	7.8
Volumes	BA (%)	77.0	20	12.0
	TEM (cm^3)	233.4	201.8	134.5
	rTEM (%)	28.4	19.9	16.0

Table 5. Agreement according to Bland-Altman test and TEM and rTEM values for surface areas and volumes.

<<TABLE 5 FOOTNOTE>>rTEM = relative technical error of measurement.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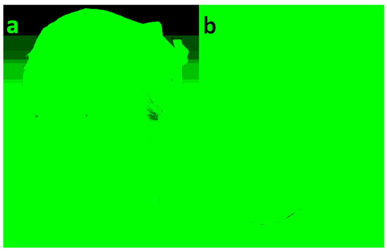
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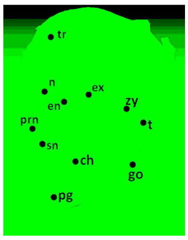
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