Evaluation of the Accuracy, Reliability, and Reproducibility of Two Different 3D Face-Scanning Systems

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Purpose: To compare the accuracy, reliability, and reproducibility of a structured light scanning system and a stereophotogrammetry scanning system on human faces. ***Materials and Methods:*** A total of 10 healthy volunteers were included in this study. After marking of facial anatomy points, their faces were scanned by a structured light scanning system and a stereophotogrammetry system, and three-dimensional (3D) images were reconstructed with corresponding software. For each volunteer, scanning was performed twice after calibration. Linear measurements were calculated and compared for the two scanning techniques with direct caliper measurements. Absolute errors (AE), absolute percentage errors (APE), and intraclass correlation coefficients (ICC) were chosen as indices to determine the accuracy, reliability, and reproducibility of the two systems. ***Results:*** There was no statistically significant difference among the three measuring techniques ($.891 < P < .999$). Both scanning systems demonstrated high accuracy (AE = 0.58 ± 0.37 mm and APE = 1.11 ± 0.73% for the structured light system; AE = 0.62 ± 0.39 mm and APE 1.17 ± 0.71% for the stereophotogrammetry system). The two systems demonstrated extremely high reliability compared to caliper measurement (0.982 < ICC < 0.998 for the structured light system; 0.984 < ICC < 0.999 for the stereophotogrammetry system). In addition, high reproducibility was observed with the two systems (0.981 < ICC < 0.999 for the structured light system; 0.984 < ICC < 1.000 for the stereophotogrammetry system). ***Conclusion:*** When applied in scanning and measuring human faces, the structured light scanning system and stereophotogrammetry scanning system both demonstrated high accuracy, reliability, and reproducibility. *Int J Prosthodont 2016;29:213–218. doi: 10.11607/ijp.4397*

In the 1990s, computer-aided design/computer-assisted manufacturing (CAD/CAM) techniques were introduced into the field of facial prostheses, greatly simplifying their fabrication. Three-dimensional (3D) scanning and reconstruction of the human facial soft tissue play a key role in digital restoration of facial defects. 3D scanning is widely used in oral and maxillofacial surgery, orthodontics, prosthodontics, plastic surgery, forensic medicine, anthropology, and esthetics. Different 3D scan techniques, including computed tomography (CT), laser scanning, structured light technology, stereophotogrammetry, and moiré topography may all be used to acquire 3D facial data.[1] Although the accuracy, reliability, and reproducibility of these techniques have been determined,[2–5] none of them completely meet the requirements for fabrication of optimal facial prostheses. Therefore, the characteristics of different 3D scanning methods are of significant interest. Coward et al compared the accuracy of 3D computer-generated ear images from CT, magnetic resonance imaging, and laser scanning.[6] Using fresh cadaver heads as objects, Fourie et al evaluated the accuracy and reliability of anthropometric linear measurement made from three different 3D scanning systems, namely laser scanning (Minolta Vivid900, Konica), cone beam computed tomography (CBCT), and stereophotogrammetry (Di3D, Direct Dimensions).[7] Using plastic mannequin heads as research subjects, Weinberg et al compared craniofacial measurement accuracy obtained by a structured light system (Genex) and a stereophotogrammetry system (3dMD).[8] However, compared to stationary objects, cadaver heads, and plastic models, human facial tissue

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Table 1 Facial Landmarks

Landmark	Abbreviation
Midline landmarks	
Nasion	N
Pronasale	Prn
Subnasale	Sn
Pogonion	Pg
Bilateral landmarks	
Exocanthion	Ex (r), Ex (l)
Endocanthion	En (r), En (l)
Orbitale	Or (r), Or (l)
Zygion	Zy (r), Zy (l)
Alare	Al (r), Al (l)
Cheilion	Ch (r), Ch (l)

r = right; l = left.

is distinct in that the soft tissue is hard to maintain in an immobile state due to activity of the facial muscles. As of the publication of this article, the accuracy, reliability, and reproducibility of face scanning systems based on structured light technology and stereophotogrammetry on the human face has not been reported. The purpose of this study was to compare the accuracy, reliability, and reproducibility of a structured light scanning system and a stereophotogrammetry system when scanning human faces.

Materials and Methods

Ten healthy volunteers (5 men and 5 women) ranging in age from 23 to 30 years without maxillofacial tumor or deformity were included in this study. Ethical approval was granted by the School of Stomatology, Peking University, and all volunteers provided informed consent.

Based on the research of Fourie et al[7] and de Menezes et al,[9] 16 landmarks (4 midline and 12 bilateral) (Table 1) were used and 21 linear measurements were calculated (Table 2). All landmarks except exocanthion and endocanthion were marked with stickers depicting black rings and centers on a white background as the black centers were easily identified in scanning 3D images. It was difficult to keep the stickers still on exocanthion and endocanthion because of eyelid twitching. Fortunately, these two landmarks could be easily identified on scanning images. All the landmarks were marked by the same person (H.Y.).

The volunteers took a seated position with teeth in the maximum intercuspal position, keeping their eyes straight ahead and with a relaxed natural expression. Faces were scanned using the structured light scanning system (3D CaMega, BWHX) and the stereophotogrammetry system (3dMD), and 3D images were reconstructed with corresponding software. For each volunteer, the scanning procedures were performed twice after calibration.

Physical measurements of the 21 linear measurements were performed with a vernier caliper (accuracy: 0.01 mm). The measuring tip of the vernier caliper lightly touched but did not press against the stickers, so as not to deform the soft tissue. For each linear measurement, the mean of the three separate measurements was calculated. From 3D images from the structured light scanning and stereophotogrammetry systems, the 21 linear measurements were obtained using the corresponding software according to the manufacturer's recommendations. Here, too, the mean of three independent measurements was used. After being marked with stickers, each volunteer underwent scanning with the two systems, and physical measurements were performed sequentially and consecutively. All measurements were performed by the same person (H.Y.).

Data were analyzed using SPSS 18.0 (IBM), and the level of significance was set at $\alpha = .05$. The mean and standard deviation (SD) for each of the 21 linear measurements were calculated for the three measuring techniques (eg, direct caliper, structured light scanning, and stereophotogrammetry). For each linear measurement, one-way analysis of variance (ANOVA) was used to evaluate measurement difference across techniques. In this process, the linear measurement values of 3D images for both scanning systems were calculated as the means of the values from the first and second scanning images. To evaluate consistency and reliability, the intraclass correlation coefficient (ICC) for absolute agreement based on a two-way random-effects ANOVA was calculated.[7] Consistency and reliability were high when the ICC was > 0.80, per the suggestion of Landis and Koch.[10] The accuracy of each scanning system was expressed in terms of absolute errors (AE) and absolute percentage errors (APE). Absolute error was defined as the measuring value in corresponding software minus the reference value. The reference value was the physical measurement taken with the vernier caliper. The measurement value in the corresponding software was calculated as the mean of the first and second scanning images. APE was calculated using the following equation: APE = (AE/reference value) × 100%. The mean and SD of linear measurements for the first and second scanning images from both scanning systems were calculated. To compare the reproducibility of the scanning system, paired *t* test and ICCs of the repeated measurements were calculated.

Results

Clear 3D color images were obtained by both scanning systems (Fig 1) in which the center of each sticker was easily identifiable.

Table 2 Values (Mean ± SD) of the Linear Measurements for the Three Measuring Techniques and ANOVA

Linear measurement	Vernier caliper (mm)	Structured light (mm)	Stereophotogrammetry (mm)	*P*
Ex (r)–Ex (l)	99.36 ± 5.37	99.20 ± 5.42	99.33 ± 5.67	.998
En (r)–En (l)	35.94 ± 2.62	35.82 ± 2.48	35.78 ± 2.13	.987
Zy (r)–Zy (l)	125.66 ± 7.20	125.80 ± 7.23	124.96 ± 6.87	.961
Ch (r)–Ch (l)	52.32 ± 4.97	52.05 ± 5.16	51.43 ± 5.17	.924
N–Sn	54.91 ± 4.48	55.16 ± 4.58	54.78 ± 4.59	.983
Sn–Pg	53.21 ± 7.07	53.32 ± 7.17	53.22 ± 7.26	.999
N–Pg	106.85 ± 8.90	107.22 ± 9.00	106.81 ± 8.92	.994
N–Zy (r)	73.16 ± 5.22	72.98 ± 5.28	72.56 ± 5.00	.965
N–Zy (l)	71.55 ± 4.38	71.72 ± 4.22	71.15 ± 4.03	.953
Sn–Zy (r)	74.02 ± 5.84	74.09 ± 5.66	73.71 ± 5.52	.987
Sn–Zy (l)	71.36 ± 4.36	71.37 ± 3.89	70.81 ± 3.68	.938
Pg–Zy (r)	103.10 ± 7.28	103.31 ± 7.36	102.95 ± 7.15	.994
Pg–Zy (l)	100.71 ± 5.99	100.50 ± 5.60	100.55 ± 5.51	.996
Al–Prn (r)	25.11 ± 2.53	25.15 ± 2.61	24.91 ± 2.46	.975
Al–Prn (l)	25.10 ± 2.85	25.41 ± 2.96	25.06 ± 2.82	.956
Sn–Ch (r)	36.39 ± 3.25	36.12 ± 3.46	35.91 ± 3.37	.950
Sn–Ch (l)	35.91 ± 3.23	35.81 ± 3.00	35.47 ± 3.15	.947
Or–Ch (r)	56.00 ± 5.73	55.83 ± 5.85	55.39 ± 5.67	.970
Or–Ch (l)	55.85 ± 4.84	55.60 ± 4.73	55.29 ± 4.56	.964
Or–Zy (r)	32.78 ± 4.69	32.60 ± 4.99	32.09 ± 4.88	.946
Or–Zy (l)	31.94 ± 4.06	31.49 ± 4.24	31.05 ± 4.20	.891

See Table 1 for abbreviations.

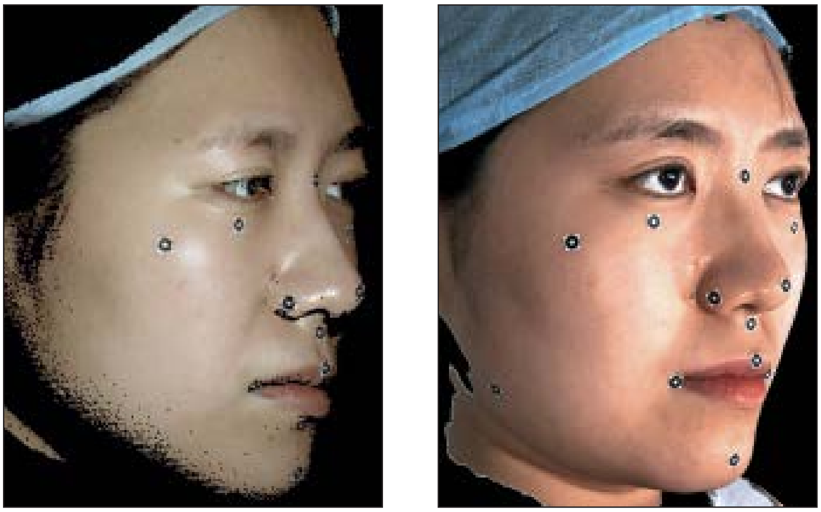

Fig 1 3D images scanned by structured light scanning **(left)** and stereophotogrammetry **(right)**

The mean and SD of the 21 linear measurements for the three measuring techniques are presented in Table 2. There was no statistically significant difference among the measurement values using the three measuring techniques (.891 < *P* < .999). Compared with physical measurement with calipers, a high degree of consistency and reliability was observed for both scanning systems (0.982 < ICC < 0.998 for structured light; 0.984 < ICC < 0.999 for stereophotogrammetry) (Table 3).

The AEs and APEs of the two scanning techniques are presented in Table 4. The mean AEs of the structured light and stereophotogrammetry systems were 0.58 ± 0.37 mm and 0.62 ± 0.39 mm, respectively, while their mean APEs were 1.11 ± 0.73% and 1.17 ± 0.71%, respectively, indicating that the accuracy of both scanning systems is high. All the AEs were below 1 mm except the value of Ch(r)–Ch(l) for the stereophotogrammetry system (Fig 2).

Table 3 Evaluation of Consistency and Reliability of the Two Scanning Techniques

Linear measurement	Structured light	Stereophoto-grammetry
Ex (r)–Ex (l)	0.998	0.998
En (r)–En (l)	0.985	0.984
Zy (r)–Zy (l)	0.996	0.996
Ch (r)–Ch (l)	0.990	0.984
N–Sn	0.998	0.998
Sn–Pg	0.998	0.999
N–Pg	0.998	0.999
N–Zy (r)	0.997	0.994
N–Zy (l)	0.997	0.992
Sn–Zy (r)	0.997	0.996
Sn–Zy (l)	0.984	0.985
Pg–Zy (r)	0.997	0.997
Pg–Zy (l)	0.995	0.993
Al–Prn (r)	0.992	0.995
Al–Prn (l)	0.991	0.998
Sn–Ch (r)	0.984	0.986
Sn–Ch (l)	0.982	0.992
Or–Ch (r)	0.995	0.996
Or–Ch (l)	0.997	0.994
Or–Zy (r)	0.997	0.993
Or–Zy (l)	0.994	0.985

Intraclass correlation coefficient values.

Table 4 Absolute Error (AE) and Absolute Percentage Error (APE) of the Two Scanning Techniques Compared with Caliper Measurements

Linear measurement	Structured light (mean ± SD, mm)		Stereophotogrammetry (mean ± SD, mm)	
	AE	APE	AE	APE
Ex (r)–Ex (l)	0.46 ± 0.24	0.46 ± 0.23	0.40 ± 0.31	0.40 ± 0.32
En (r)–En (l)	0.53 ± 0.33	1.49 ± 0.91	0.44 ± 0.39	1.21 ± 1.03
Zy (r)–Zy (l)	0.76 ± 0.61	0.61 ± 0.49	0.81 ± 0.47	0.63 ± 0.35
Ch (r)–Ch (l)	0.90 ± 0.54	1.67 ± 0.93	1.20 ± 0.46	2.27 ± 0.81
N–Sn	0.33 ± 0.27	0.59 ± 0.48	0.32 ± 0.26	0.60 ± 0.50
Sn–Pg	0.53 ± 0.33	1.02 ± 0.64	0.44 ± 0.37	0.80 ± 0.67
N–Pg	0.63 ± 0.43	0.61 ± 0.45	0.51 ± 0.41	0.49 ± 0.41
N–Zy (r)	0.51 ± 0.25	0.70 ± 0.35	0.70 ± 0.45	0.95 ± 0.60
N–Zy (l)	0.38 ± 0.24	0.54 ± 0.36	0.59 ± 0.53	0.79 ± 0.70
Sn–Zy (r)	0.47 ± 0.41	0.63 ± 0.56	0.60 ± 0.45	0.78 ± 0.53
Sn–Zy (l)	0.97 ± 0.44	1.35 ± 0.60	0.82 ± 0.61	1.13 ± 0.80
Pg–Zy (r)	0.74 ± 0.33	0.71 ± 0.29	0.69 ± 0.41	0.67 ± 0.40
Pg–Zy (l)	0.70 ± 0.43	0.69 ± 0.42	0.80 ± 0.57	0.79 ± 0.57
Al–Prn (r)	0.37 ± 0.27	1.52 ± 1.09	0.31 ± 0.21	1.23 ± 0.82
Al–Prn (l)	0.49 ± 0.25	1.93 ± 0.93	0.22 ± 0.10	0.86 ± 0.37
Sn–Ch (r)	0.61 ± 0.62	1.68 ± 1.71	0.72 ± 0.40	1.96 ± 1.09
Sn–Ch (l)	0.72 ± 0.43	2.01 ± 1.18	0.57 ± 0.32	1.58 ± 0.93
Or–Ch (r)	0.68 ± 0.51	1.25 ± 0.99	0.67 ± 0.35	1.20 ± 0.63
Or–Ch (l)	0.40 ± 0.31	0.71 ± 0.56	0.64 ± 0.27	1.14 ± 0.43
Or–Zy (r)	0.48 ± 0.25	1.48 ± 0.81	0.71 ± 0.47	2.24 ± 1.49
Or–Zy (l)	0.52 ± 0.38	1.69 ± 1.29	0.91 ± 0.46	2.91 ± 1.54
Mean	0.58 ± 0.37	1.11 ± 0.73	0.62 ± 0.39	1.17 ± 0.71

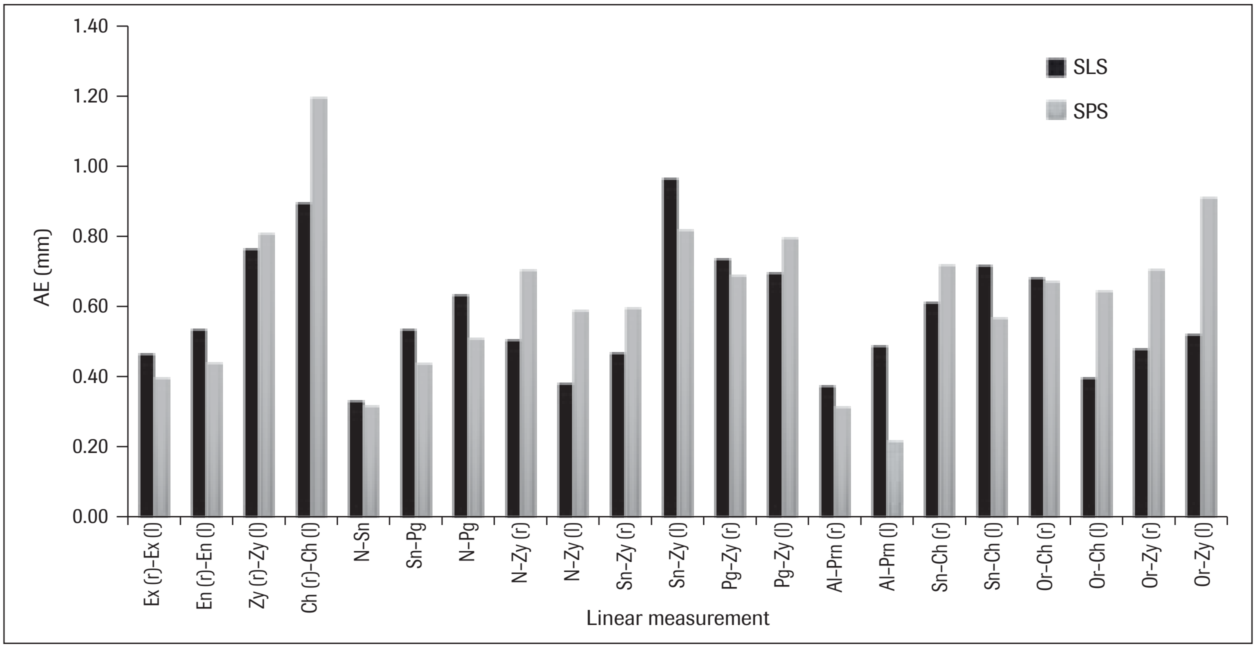

Fig 2 The absolute errors of the two scanning techniques compared with caliper measurement. SLS = structured light system; SPS: stereophotogrammetry system.

The means and SDs of linear measurements for the first and second scanning images, the *P* values of paired *t* test, and ICCs are presented in Table 5. There were no statistically significant differences between the two scans for either scanning systems ($P > .05$). Furthermore, the ICCs (0.981 < ICC < 0.999

Table 5 Linear Measurements for the First and Second Scanning Images and Their Comparison

	Structured light				Stereophotogrammetry			
Linear measurement	Test 1 (mean ± SD, mm)	Test 2 (mean ± SD, mm)	*P*	ICC	Test 1 (mean ± SD, mm)	Test 2 (mean ± SD, mm)	*P*	ICC
Ex (r)–Ex (l)	99.32 ± 5.38	99.08 ± 5.48	.324	0.996	99.28 ± 5.72	99.37 ± 5.64	.709	0.996
En (r)–En (l)	35.66 ± 2.44	35.97 ± 2.54	.087	0.986	35.88 ± 2.15	35.67 ± 2.14	.143	0.989
Zy (r)–Zy (l)	125.87 ± 7.23	125.73 ± 7.24	.479	0.998	125.07 ± 6.92	124.84 ± 6.83	.154	0.999
Ch (r)–Ch (l)	51.99 ± 5.10	52.11 ± 5.24	.605	0.995	51.51 ± 5.15	51.35 ± 5.20	.312	0.998
N–Sn	55.23 ± 4.44	55.08 ± 4.74	.470	0.996	54.62 ± 4.61	54.93 ± 4.57	.066	0.996
Sn–Pg	53.07 ± 7.06	53.56 ± 7.29	.067	0.997	53.39 ± 7.06	53.04 ± 7.48	.291	0.995
N–Pg	107.10 ± 8.82	107.33 ± 9.20	.417	0.998	106.89 ± 8.78	106.74 ± 9.09	.676	0.997
N–Z y(r)	73.03 ± 5.20	72.92 ± 5.37	.551	0.997	72.62 ± 5.05	72.50 ± 4.96	.296	0.999
N–Zy (l)	71.69 ± 4.21	71.74 ± 4.24	.796	0.996	71.21 ± 4.14	71.08 ± 3.92	.264	0.998
Sn–Zy (r)	74.04 ± 5.67	74.13 ± 5.66	.448	0.999	73.72 ± 5.62	73.69 ± 5.43	.842	0.999
Sn–Zy (l)	71.44 ± 3.97	71.29 ± 3.82	.404	0.995	70.82 ± 3.66	70.80 ± 3.71	.845	0.999
Pg–Zy (r)	103.23 ± 7.37	103.38 ± 7.36	.515	0.998	103.03 ± 7.12	102.86 ± 7.20	.524	0.997
Pg–Zy (l)	100.42 ± 5.55	100.57 ± 5.67	.509	0.997	100.35 ± 5.53	100.75 ± 5.57	.390	0.984
Al–Prn (r)	25.18 ± 2.75	25.11 ± 2.47	.517	0.995	24.90 ± 2.49	24.92 ± 2.43	.390	1.000
Al–Prn (l)	25.33 ± 3.00	25.49 ± 2.95	.455	0.988	25.09 ± 2.82	25.02 ± 2.82	.077	0.998
Sn–Ch (r)	36.11 ± 3.38	36.13 ± 3.56	.930	0.995	35.95 ± 3.34	35.87 ± 3.41	.510	0.998
Sn–Ch (l)	35.67 ± 3.12	35.94 ± 2.93	.326	0.981	35.61 ± 3.09	35.33 ± 3.23	.052	0.994
Or–Ch (r)	56.00 ± 6.00	55.66 ± 5.73	.181	0.996	55.39 ± 5.70	55.39 ± 5.65	.975	0.999
Or–Ch (l)	55.58 ± 4.82	55.62 ± 4.66	.841	0.996	55.23 ± 4.55	55.33 ± 4.59	.511	0.998
Or–Zy (r)	32.70 ± 4.81	32.49 ± 5.19	.452	0.993	32.13 ± 4.88	32.03 ± 4.89	.154	0.999
Or–Zy (l)	31.51 ± 4.18	31.45 ± 4.31	.693	0.997	31.11 ± 4.18	30.98 ± 4.23	.115	0.999

for structured light; 0.984 < ICC < 1.000 for stereophotogrammetry) indicate high reproducibility for both scanning systems for repeated measuring.

Discussion

No matter the measurement or scanning technique used, selection and correct identification of landmarks is necessary for indirect measurements on facial images. Bianchi et al[11] believed the main reason for errors between indirect measurement on images and direct physical measurements is the difficulty in marking and identifying anatomical points on images. Furthermore, some anatomical points, such as the zygion (defined as the outermost point of the zygomatic arch), are not objective. Although the zygion can be clearly identified with touch during direct physical measurement, this is not feasible with scanned images. Therefore, it is crucial to mark landmarks exactly so they can be easily and accurately identified in scanned images.

In some previous studies, researchers who selected facial landmarks directly on images attempted to reduce errors via repeated measurements and multiple measurers.[4,12] For stereophotogrammetric images, the landmarks could be clearly identified as long as their color was different from the color of the skin, since high-resolution color information can be obtained with this technique.[13] With the structured light system used in this study, the high-resolution color information could not be captured. The white object was clearly recognizable, but the black object could not be identified. Therefore, stickers with black rings and centers on a white background were used to mark landmarks, resulting in good recognition of the center point of the stickers on images scanned using the structured light system (Fig 1). As in the study done by Fourie et al, exocanthion and endocanthion were not marked with stickers because these points were difficult to mark on physical faces while relatively simple to identify on the scanned images.[7]

Since 3D face scanning is an important tool and widely used in prosthodontics, orthodontics, maxillofacial surgery, and so on, determining the accuracy, reliability, and reproducibility of scanning systems in real situations is a prerequisite for clinical application. Although black stickers were used in this study to promote the recognition of selected anatomical points during the evaluation of the accuracy, reliability, and reproducibility of 3D face scanning systems, they are not necessary for routine clinical applications, ensuring minimal complexity and inconvenience in the clinical setting.

In this study, the mean AEs of the structured light scanning system and stereophotogrammetry system were 0.58 ± 0.37 mm and 0.62 ± 0.39 mm, respectively, while the mean APEs were 1.11 ± 0.73% and 1.17 ±

0.71%, respectively. All the AEs of linear measurement were below 1 mm except the one value of Ch(r)–Ch(l) for the stereophotogrammetry system. By scanning and measuring a facial plaster model, Ma et al showed that the accuracy of the structured light scanning system (BWHX) was high, with a mean AE of 0.93 mm.[4] Khambay et al measured the linear measurement of 12 plaster facial models using a stereophotogrammetry system (Di3D) and compared the results to those of the 3D coordinate measuring instrument, the results of which indicated that the system error of this device was less than 0.2 mm.[3] Paul et al found the measuring accuracy of the stereophotogrammetry system (3dMD) was high, with errors < 1 mm through measuring the scanned images of geometric solids and a human-form mannequin.[13] Therefore, the results of this study are consistent with previously published studies in which mean AEs were far less than 1 mm. Farkas et al thought errors between indirect and direct measuring of < 1 mm were clinically acceptable.[14] The present results demonstrate that the accuracy of both systems was high enough, even for human faces.

In this study, no statistically significant difference was found among the three measuring techniques (.891 < *P* < .9991). Weinberg's research, using a plastic mannequin as object, found a statistically significant difference between the three measuring techniques but noted that the clinical relevance of the difference was negligible because errors were < 1 mm (within the acceptable range of error for clinical physical facial measurement systems).[8]

When compared with direct caliper measuring, the stereophotogrammetry system was highly consistent and reliable (0.984 < ICC < 0.999), and similar to Fourie's research using fresh cadaver heads as objects (0.928 < ICC < 0.999).[7] The structured light system also showed high consistency and reliability, but direct comparison to previous studies was not feasible due to the use of different statistical methods.[4,8]

High reproducibility for both systems was observed in this study (0.981 < ICC < 0.999). Maal's research to evaluate variations in the face using the stereophotogrammetry system (3dMD) found the mean variation was 0.25 mm when measuring the face at rest.[5] Though the research designs and statistical methods were different, the results of our study were similar to the studies of Maal and other researchers.[3,5,12,15]

Conclusions

There were no statistically significant differences among the three measuring techniques (direct caliper, structured light scanning, and stereophotogrammetry) when applied to human faces. The structured light scanning and stereophotogrammetry systems both demonstrated high accuracy, reliability, and reproducibility.

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