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An *in vitro* Comparison of Accuracy Between Three Different Face Scanning Modalities

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ABSTRACT

A mannequin head was digitized using a reference scanner (Scan in a Box) to acquire the reference mesh. Subsequently it was scanned with a structured light scanner (Einscan Pro HD), a stereophotogrammetry scanner (RayFace100) and a laser scanner (Proface 3D Mid) to acquire test meshes.Resulting meshes were delineated in four horizontal areas and discrepancies calculated for the complete face and different facial partitions. One-way Anova and pairwise comparisons tests were used to compare trueness and precision between scanners across different areas. Significant differences were detected among scanners for complete face ($F(3, 27) = 776$, $P < 0.01$)) and for delineated face areas ($F(11, 99) = 200.1$, $P < 0.01$)). Einscan had significantly higher accuracy for the complete face ($P<0.01$) and significantly higher trueness for each facial partition compared to other scanners. RayFace had significantly higher trueness when scanning the middle part of face compared to other facial parts. Proface had significantly lower upper facial third trueness compared to other facial parts. All scanners had accuracy levels below the 2.00mm threshold. Facial scanning accuracy was influenced per scanner used. Scanning trueness per device was influenced by location of surface area. All scanners had accuracy levels within the acceptable accuracy threshold.

INTRODUCTION

Three different optical scanning technologies are currently employed in the process of digitizing patients' facial tissue, namely stereophotogrammetry, laser scanning and structured light scanning.[1,2] Stereophotogrammetry devices capture surface images of the face from multiple single-lens reflex cameras producing highly realistic, detailed, colored models with sufficient skin texture. However, the accuracy of the reconstructed images greatly depends on parameters such as pixel integrity and scanner resolution.[2,3] Additionally, strong direct ambient light during image capturing may provoke a glare effect that dismisses the details of surface reconstruction.[4] Laser and structured light scanners, on the other hand, have different working principles. Laser scanners project a laser point or line onto the surface and capture its reflection with dedicated sensors.[5] Structured light scanners project pattern light onto the object and record its deformation with cameras.[6] Using triangulation principles, the x,y and z coordinates of the surface point can be determined and the 3D geometry of the face can thus be reconstructed.

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These scanning modalities are commercially available in two different device set-ups, mainly portable as opposed to stationery scanners. Stationery structured light scanners often lack adequate surface coverage therefore several captures from different angles are needed for complete facial data.[7] This has led to the development of portable, handheld structured light scanners. Motion artefacts in portable facial scanners when scanning real patients have been reported in the literature mainly due to extended acquisition times[7,8] but the acquisition and fusion of multiple scans in a structured light scanner can lead to lower scanning errors.[9,10] Stereophotogrammetry facial scanners are advantageous in that they are stationery, rapid and with expanded surface coverage of more than 180° that minimizes possible motion artefacts due to patient movements.[11] Laser scanners also exhibit relatively slow acquisition times that makes them vulnerable to voluntary and involuntary patient movements.[12] A recent meta-analysis, however, suggested that there is no statistical significant difference in the accuracy of portable versus stationary scanning systems.[13] Also, within the comparison of the portable systems, no statistically significant differences in accuracy were detected among different scanning modalities.[13]

According to the ISO international standard number 5725, trueness is the ability of a measurement or measuring device to match the actual value of the quantity being measured, whereas precision is the ability of a measurement or measuring device to consistently repeat a particular measurement. Trueness and precision are both measures of accuracy. Regarding the accuracy of facial scanning systems, literature suggests that facial scanners, in general, deviate in the range of 140 to 1330 μm with an average accuracy of 500 μm.[14] Although there is not a current consensus in the literature regarding accuracy thresholds for facial scanners, a discrepancy of up to 2.00 mm is considered to be within the acceptable clinical range.[15] According to Mai and Lee (2020), the reliability of a digital face scanner system can be classified into four categories: highly reliable (deviation<1.00 mm), reliable (deviation 1.00-1.50 mm), moderately reliable (deviation 1.50-2.00 mm) and unreliable (deviation >2.00 mm).[16]

Regarding the ability of different scanning modalities to accurately depict different anatomical facial structures, literature is somewhat inconclusive as a result of differences attributed to optical device technology, study design and sample, inanimate or live patient population. In general, laser scanners are deemed not sensitive enough to visualize deeper anatomical indentations such as nostrils,[5,10] undercuts in maxillofacial defects[17] or indentations deeper than 2.00 mm with a 6.00 mm or lower diameter.[18] Due to relatively longer acquisition times compared to other facial scanning technologies, laser scanners have been reported to be prone to inaccuracies related to patient movements especially in the linear distances between the exocanthion, endocanthion and gnathion facial landmarks[19] and handheld laser scanner devices, in particular, should only be used when scanning inanimate subjects.[20] Depending on the specific device used, structured light scanners have been shown to scan more accurately the upper face,[21] exhibited the same accuracy when scanning the forehead and cheek areas[22] or deviated statistically significantly in linear measurements between the left and right exocanthion craniofacial landmarks.[23] Stereophotogrammetry scanners have shown statistically significantly higher accuracy in the middle face,[21] whereas in other studies have deviated more than 1.00 mm in the measured distances between the left and right cheek craniofacial landmarks[24] and left and right exocanthion landmarks.[25]

The purpose of the present *in vitro* study was to investigate discrepancies in accuracy among three different facial scanning modalities when scanning an inanimate mannequin head and also the influence of the scanned facial area in the accuracy of these three systems. Two null hypotheses were formulated. The first null hypothesis was that there is no statistically significant difference in accuracy between scanners when scanning the complete face. The second null hypothesis was that there is no statistically significant difference in accuracy between scanners when scanning different areas of the face.

MATERIALS AND METHODS

A mannequin head (intubation trainer head;Karl Storz endoscope, Tuttlingen, Germany) was obtained. A positioning base was 3d-printed from polylactic acid material (PLA; MCPP Netherlands BV, Helmond, The Netherlands) to facilitate a stable vertical position of the head with the maxillary occlusal plane parallel to the horizontal plane. Nine stainless steel spheres with a 4.00 mm diameter were firmly secured with cyanoacrylate adhesive (Super Glue Control; Bison International BV, Rotterdam, The Netherlands) in the following positions on the face: left, right and center forehead, glabella, tip of nose, left and right zygomatic, diastema between the incisal edges of upper central incisors and pogonion. The face and spheres were sprayed with a uniform thin layer of anti-reflex aerosol (Mr 2000 anti-reflex L; mr Chemie, Unna, Germany) to reduce the reflective index of both the silicone of the mannequin head and of the metal spheres. Sample size estimation was performed with the use of G*Power 3.1.9.6 statistical software (https://www.psychologie.hhu.de/). A sample size of 10 scans per group was calculated for an estimated effect size f(V) = 0.6, an α error probability of 0.95 and a power of 0.8.

The mannequin head was digitized ten times by using a high accuracy white LED structured light scanner (Scan in a Box; Open Technologies SLR; Rezzato, Italy) with two 2-megapixel cameras, a field of view of up to 500x400 mm and accuracy of 78 μm as reported by the manufacturer, to produce the reference meshes *(Figure 1)*. Scanning was undertaken under constant ambient lighting conditions at 400 lux using a light meter (UT383; Uni-Trend Technology Limited; Dongguan; China). The scanner was calibrated according to the manufacturer's instructions at the beginning of the scanning session. The head was then placed on an automatic turntable and the digitization process was completed in a single session. All scans were post-processed and exported in the standard tessellation language (STL) file format.

Figure 1: Mannequin head scanned with reference scanner.

The mannequin head was then scanned ten consecutive times by a structured light scanner (Einscan Pro HD, SHINING 3D, Hangzhou, China) using the scanning parameters shown in Table 1 under constant ambient lighting conditions of 400 lux, measured using the same light meter. The handheld scanner was rotated around the head until the complete face was digitized *(Figure 2)*. Each scan duration was approximately 60 seconds. All scans were post-processed, exported in STL file format and coded (Einscan). Next, the head was positioned into the laser scanner (Proface 3D Mid; Planmeca; Helsinki, Finland) using the positioning jig *(Figure 3)* and scanned ten consecutive times using the scanning parameters shown in Table 1 under constant ambient lighting conditions (400 lux). Each scan duration was approximately 15 seconds. All scans were post-processed, exported in STL file format and coded (Proface). Finally, the mannequin head was positioned in front of the stereophotogrammetry scanner (RayFace100; Ray Co Ltd, Gyeonggi-do, Korea) according to the manufacturer's instructions *(Figure 4)*. The head was scanned ten times using the scanning parameters shown in Table 1 under constant ambient room lighting conditions at 400 lux. All ten scans were post-processed in HD mode, exported as STL files and coded (RayFace). Lighting conditions were regulated using fluorescent lamps (18W, 6500K) mounted on the roof of the operatory and constantly monitored using the light meter in an effort to simulate stable clinical operatory conditions.

Figure 2: Mannequin head scanned with the Einscan Pro HD scanner.

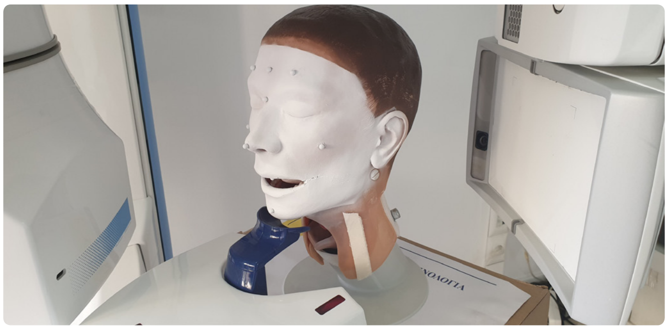

Figure 3: Mannequin head scanned with the Proface 3D Mid scanner.

Table 1. Scanning parameters used with each face scanner.

Scanner	Scanning parameters
Einscan PRO HD	Texture: Non-texture scan, Mode of alignment: Features, Operation mode: High detail, Resolution: High
Planmeca ProFace 3D Mid	3D photo FOV (HxWxD): 230x190x200mm 3D photo surface resolution: 500x500 points LED illumination 1100 lux Laser class 1
RayFace	White balance: 5900K Brightness scale: 9/10 Scan type: Smile

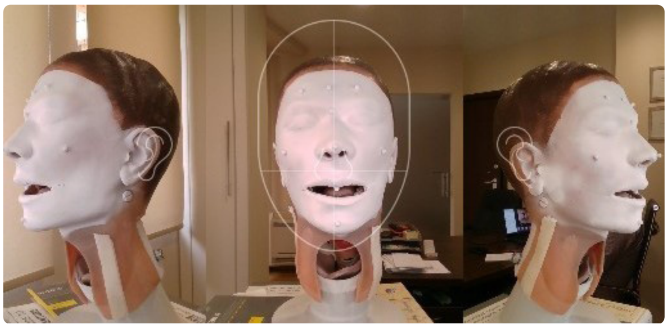

Figure 4: Mannequin head scanned with the RayFace scanner.

The accuracy of the face scanners was estimated by computing their trueness and precision. Scanning trueness for each device was estimated in 3 different instances. Initially, trueness was estimated on the complete face (*Figure 5*). Next, the face was divided into 3 horizontal partitions consisting of the upper (part of head just below the eyes including the glabella), middle (part of head approximately 1.00 cm above the vermilion of the upper lip including the nose) and lower (part of head including the pogonion) thirds (*Figure 6*). Scanning trueness was estimated for each separate horizontal facial partition. Finally, trueness was estimated for the mouth area. This area was defined bilaterally, approximately 1.00 cm from the corner of the mouth and approximately 1.00 cm from the upper border of the upper lip and 1.00 cm from the lower border of the lower lip. (*Figure 7*).

Figure 5: STL meshes of the complete face from all scanners tested. From left to right: Reference STL, RayFace100 STL, Einscan STL and Proface STL.

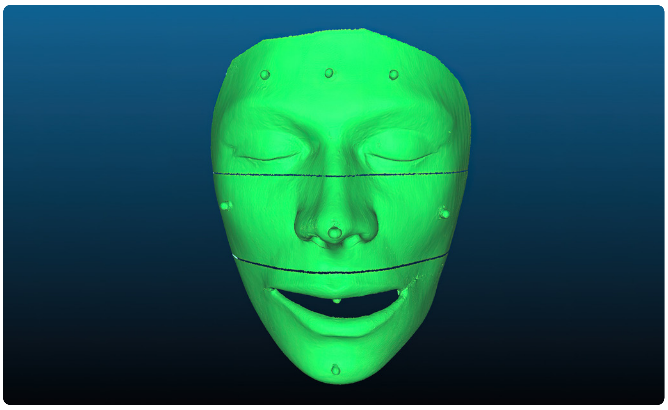

Figure 6: Horizontal partitioning of the face.

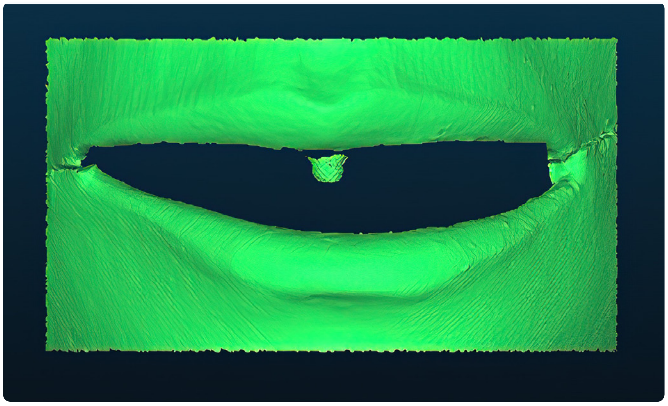

Figure 7: Mouth area partition.

For each of the test scanners, 10 meshes were imported for computational manipulation in a dedicated mesh and point cloud handling software (CloudCompare, version 2.20.2 Zephyrus; Anoia). The accuracy of this software has been verified by the authors in a previous study.[26] This resulted in a total of 30 test meshes.

The 30 test-originated meshes and the reference mesh were then initially roughly registered together using a minimum (3–5) number of points and then again finely registered with each other using the iterative closest point (ICP) algorithm, calculated on a sample of 50,000 pairs of points. This resulted in 31 meshes overlapping one another. The test meshes and the reference mesh were then simultaneously cropped leaving most of the face intact (*Figure 8*). The result was 31 triangular meshes (3 test groups with 30 test meshes in total and 1 reference mesh) with clinically relevant remaining anatomy, identical for each mesh. Finally, each of the 30 test meshes was again separately, roughly, and finely registered to the gold standard. For each test mesh registered to the reference mesh, the absolute distance of each face of the mesh to a point on the surface of the reference was computed indicating the difference that exists between this mesh and the reference mesh. The mean value of the differences and the standard deviation (SD) for each pair was noted. These mean values were used for the estimation of trueness for the complete face area.

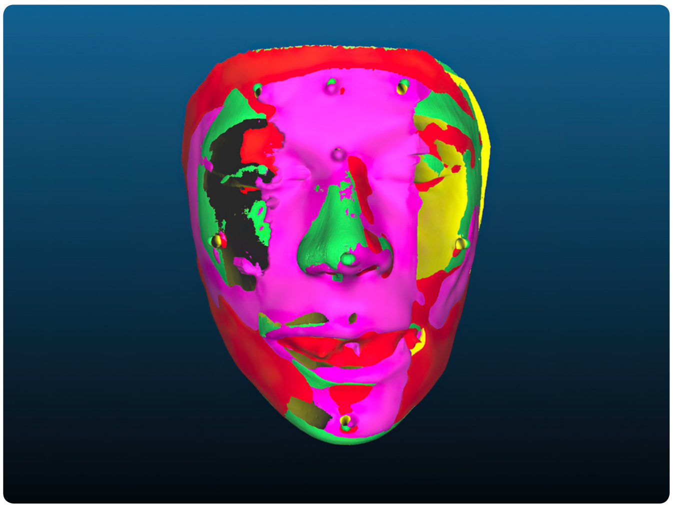

Figure 8: Reference and test STLs aligned to one another and simultaneously cropped.

Next, the complete face was separated in 3 horizontal parts. This resulted in 3 groups of triangular meshes, with each group including the 30 test meshes of the relevant partition (upper, middle and lower) and the corresponding reference mesh of the same area. Finally, each of these meshes was again separately, roughly, and finely registered to the relevant part of the reference mesh. Again, for each test mesh registered to reference mesh, the absolute distance of every face of the mesh to a point on the surface of the reference standard was computed indicating the difference that existed between this mesh and the reference. The mean value of the differences and the standard deviation (SD) for each pair was noted. Again, these mean values were used for the estimation of the trueness of the scanners for each separate third of the face.

Finally, the mouth area was segmented. The same process for mesh registration as described above for the segmentation of the facial thirds was followed. Trueness of the scanners for the area of the mouth was estimated using the mean values of the differences of the mouth area between the test scanners and the reference one.

STATISTICAL ANALYSIS

Descriptive statistics were calculated, and inferences were drawn using repeated measures one-way ANOVA with fixed factor 'Face Scanner Model' and dependent variable 'The difference between the test scanner and the reference'. Results were considered significant for a Bonferroni corrected p <0.05.

In order to estimate the precision of the face scanners, the ten meshes (for each face scanner) were simultaneously roughly and then finely registered with each other, following the same procedure as described for the estimation of trueness. Each of the meshes registered was sequentially used as a reference, resulting in a total of 90 pairs of meshes. The average standard deviation (SD) of the differences of the pairs of the meshes was used as a measure of precision. Inferences were drawn using repeated measures one-way ANOVA with fixed factor 'Face Scanner Model' and dependent variable 'The average SD of differences of the pair of the meshes'. Results were considered significant for a Bonferroni corrected p <0.05. SPSS version 28 (IBM; New York, USA) was used for the statistical analysis.

RESULTS

The dependent variable 'The difference between the test scanner and the reference', was normally distributed at each scanner group, as assessed by Shapiro-Wilk's test (p >0.05). Trueness of the face scanners for the complete face are shown in Table 2 and Figure 9. One-way repeated measures ANOVA revealed that differences existed between the imaging modalities (F (3, 27) =776, p <0.01). Pairwise comparisons revealed that the Einscan Pro HD device had a significantly smaller error than the rest of the scanners (p<0.01 for both RayFace and Proface 3d Mid), followed by RayFace with a significant smaller error than the Proface 3D Mid (p <0.01). Finally, the Proface 3D Mid had statistically significantly less trueness (p <0.01) compared to all tested scanners, concerning the complete face (*Table 3*).

Regarding trueness values of the face scanners in the upper, middle and lower facial partitions, results are depicted in Table 2 and Figure 10. For the mouth area, trueness values for the face scanners tested are shown in Table 2 and Figure 11. Familywise one-way repeated measures ANOVA revealed that differences existed between the 3 imaging modalities (12 instances) (F (11, 99) =200.1, p <0.01)).

Pairwise comparisons revealed that for the Einscan Pro HD structured light scanner, the upper facial third had statistically significantly higher trueness than the middle third (p <0.01), but no statistically significant differences were detected between the upper and the lower thirds (p = 0.11) or the mouth area (p = 1.00). The lower third facial partition had statistically significantly higher trueness than the middle third (p <0.01) but not compared to the mouth area (p = 1.00). Concerning the RayFace stereophotogrammetry device it was revealed that the middle third facial partition was scanned with statistically significantly higher accuracy compared to all the other parts of the face (p <0.01). Finally, for the Proface 3D Mid laser scanner it was revealed that the upper third facial partition was scanned with statistically significantly lower trueness compared to all the other areas tested (p <0.01). Pairwise comparisons are presented in detail in Table 4.

Regarding scanning precision of the tested scanners, values are depicted in Table 2 and Figure 12. One-way repeated measures ANOVA revealed that differences existed between the 3 imaging modalities (F (3, 27) =1301, p <0.01). Pairwise comparisons revealed that the Einscan Pro HD device had a statistically significantly higher precision compared to both the RayFace and the Proface 3D Mid devices (p <0.01). Finally, the Proface 3D Mid scanner was statistically significantly less precise than the rest of the devices tested (p <0.01) (*Table 3*).

Table 2. Trueness and Precision of Scanners (mm).

	Complete Face Trueness		Upper Facial 3rd Trueness		Middle Facial 3rd Trueness		Lower Facial 3rd Trueness		Mouth area Trueness		Complete Face Precision
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Einscan	0.359	0.0147	0.2569	0.0192	0.3166	0.0061	0.2785	0.0077	0.2469	0.0478	0.009
RayFace	0.968	0.0118	0.9926	0.0404	0.5347	0.0709	1.0438	0.1376	0.9502	0.1432	0.017
Proface	1.301	0.0885	1.684	0.239	1.0269	0.0327	1.0347	0.0587	1.0145	0.0702	0.165

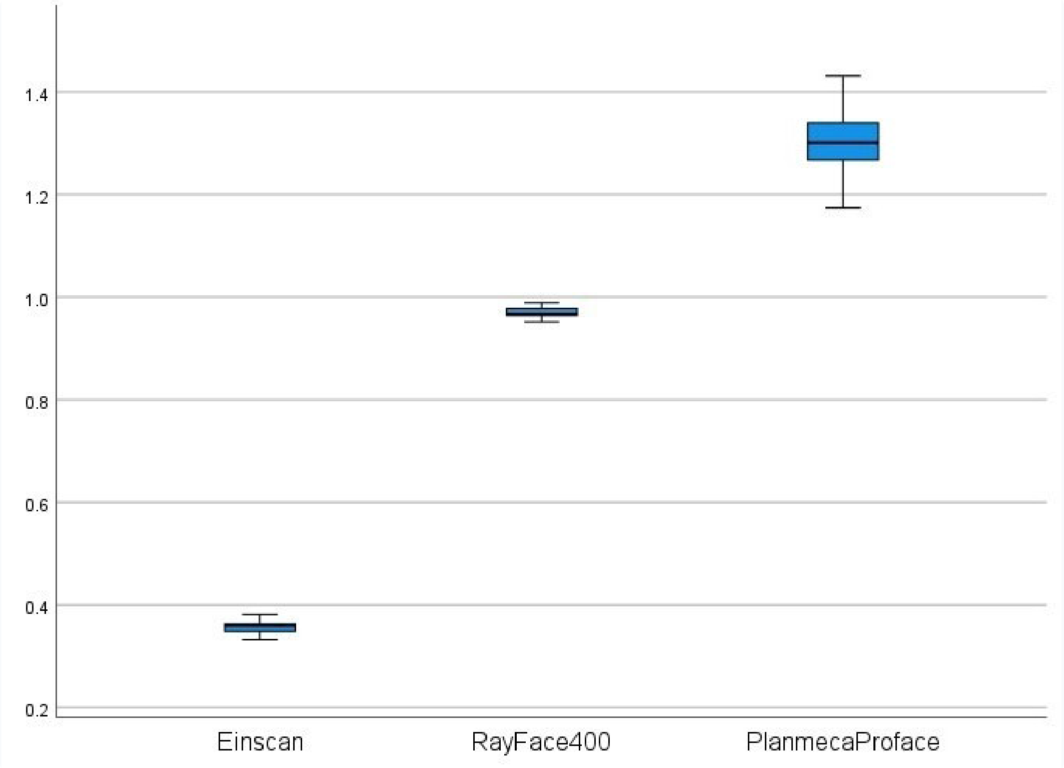

Figure 9: Complete face trueness (mm).

Table 3. Pairwise comparisons (trueness and precision) for complete face.

		Trueness	Precision
		Mean Difference	**Mean Difference**
Einscan	RayFace	-.609*	-.008*
	Proface	-.942*	-.156*
RayFace	Einscan	.609*	.008*
	Proface	-.333*	-.148*
Proface	Einscan	.942*	.156*
	RayFace	.333*	.148*

*** denotes a significant difference**

DISCUSSION

Statistically significant differences in scanning accuracy between the three facial scanning modalities were found for both the complete face and for the separate thirds of the face (upper, middle and lower), therefore both null hypotheses had to be rejected.

Regarding complete face scanning trueness, the Einscan Pro HD scanner exhibited a mean value of 0.358 mm at 400 lux which is not in agreement to the mean accuracy value of 0.02 mm reported by the manufacturer for the scanning parameters used. In a recent *in vitro* study by Thongma-Eng *et al* (2022), the Einscan Pro X2 Plus face scanner presented statistically significant differences in accuracy in various ambient light settings.[27] Scanning under 500 lux resulted in the highest accuracy, exhibiting a complete face trueness of 0.077 mm, a value which is not in agreement with the results of the present study. This can be attributed to the different version of the scanner that was used (Pro X2 plus as opposed to Pro HD). In the present study, the structured light scanner presented statistically significantly higher trueness compared to all other scanning modalities tested. In particular, the Einscan Pro HD structured light scanner had statistically higher trueness than the Proface 3D Mid laser scanner (mean 1.301 mm), a finding that has also been reported in the study by Amornvit and Sanohkan (2019)[18] although in the latter study,

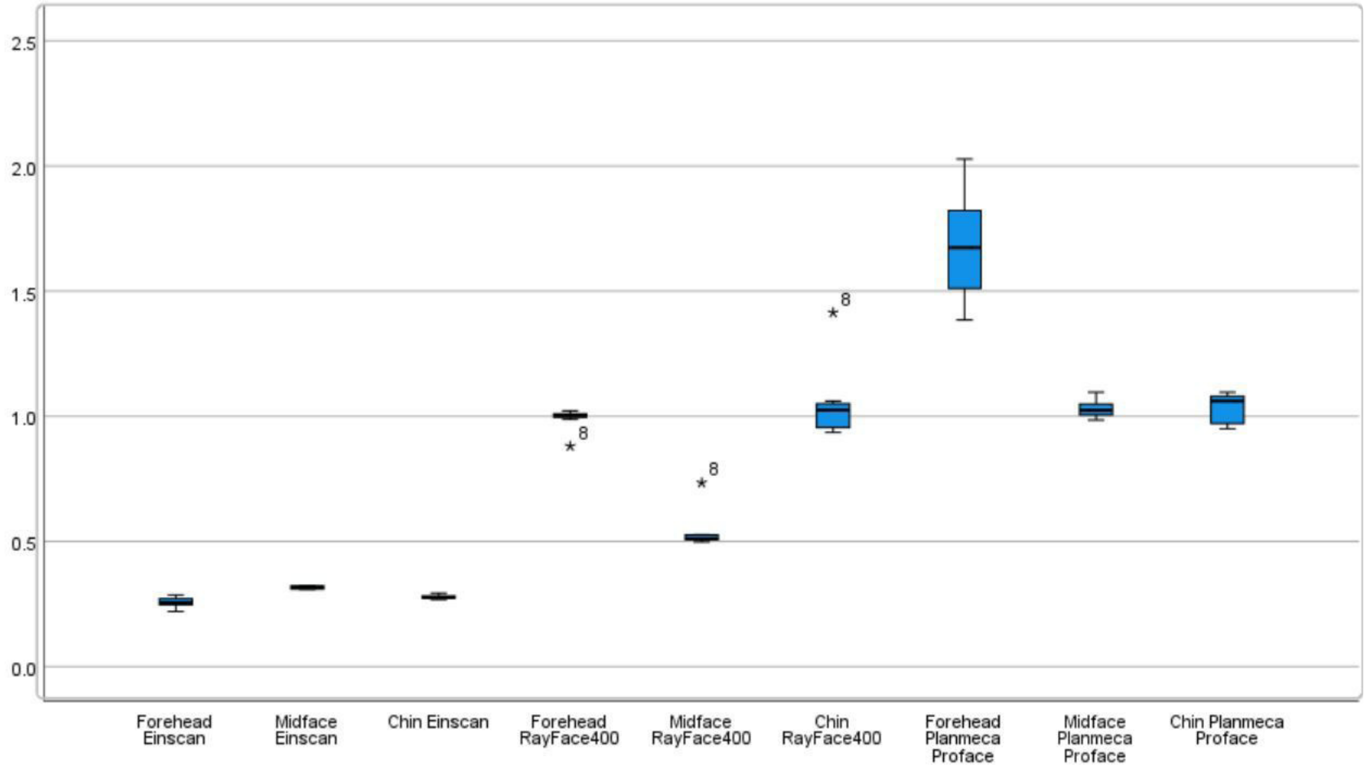

Figure 10: Upper, middle and lower facial thirds trueness (mm).

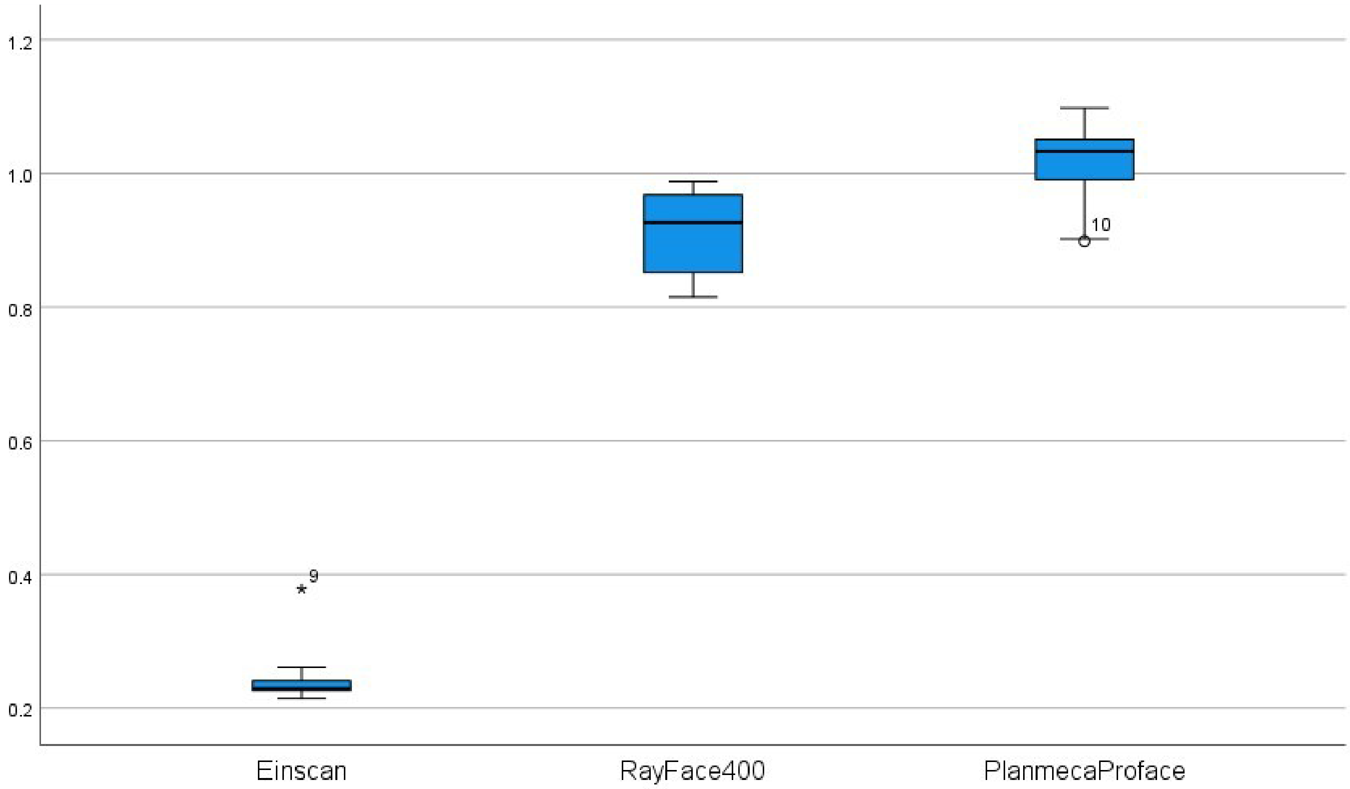

Figure 11: Mouth area trueness (mm)

measurements between arbitrary facial landmarks were utilized instead of 3d surface measurements. The complete facial scanning accuracy of the Proface 3D Mid laser scanner utilizing reference anthropometric measurements has been reported in the literature.[19,28,29] In an *in vivo* study by Menendez Lopez-Mateos *et al* (2019),[28] the mean error in accuracy for the Planmeca scanner when compared to direct anthropometric measurements was 1.04 mm. In another *in vivo* study by Liberton *et al* (2019), the

Table 4. Trueness familywise & pairwise comparisons.

Model		Mean Difference	Sig.
Upper Einscan	Upper RayFace	-.736*	0,000
	Upper Proface	-1.427*	0,000
	Middle Einscan	-.060*	0,000
	Middle RayFace	-.278*	0,000
	Middle Proface	-.770*	0,000
	Lower Einscan	-0,022	0,110
	Lower RayFace	-.787*	0,000
	Lower Proface	-.778*	0,000
	Mouth Einscan	0,010	1,000
	Mouth RayFace	-.693*	0,000
	Mouth Proface	-.758*	0,000
Upper RayFace	Upper Einscan	.736*	0,000
	Upper Proface	-.691*	0,000
	Middle Einscan	.676*	0,000
	Middle RayFace	.458*	0,000
	Middle Proface	-0,034	1,000
	Lower Einscan	.714*	0,000
	Lower RayFace	-0,051	1,000
	Lower Proface	-0,042	1,000
	Mouth Einscan	.746*	0,000
	Mouth RayFace	0,042	1,000
	Mouth Proface	-0,022	1,000
Upper Proface	Upper Einscan	1.427*	0,000
	Upper RayFace	.691*	0,000
	Middle Einscan	1.367*	0,000
	Middle RayFace	1.149*	0,000
	Middle Proface	.657*	0,001
	Lower Einscan	1.405*	0,000
	Lower RayFace	.640*	0,013
	Lower Proface	.649*	0,000
	Mouth Einscan	1.437*	0,000
	Mouth RayFace	.734*	0,006
	Mouth Proface	.670*	0,001
Middle Einscan	Upper Einscan	.060*	0,000
	Upper RayFace	-.676*	0,000
	Upper Proface	-1.367*	0,000
	Middle RayFace	-.218*	0,000
	Middle Proface	-.710*	0,000
	Lower Einscan	.038*	0,000
	Lower RayFace	-.727*	0,000
	Lower Proface	-.718*	0,000
	Mouth Einscan	0,070	0,104
	Mouth RayFace	-.634*	0,000
	Mouth Proface	-.698*	0,000
Middle RayFace	Upper Einscan	.278*	0,000
	Upper RayFace	-.458*	0,000
	Upper Proface	-1.149*	0,000
	Middle Einscan	.218*	0,000
	Middle Proface	-.492*	0,000
	Lower Einscan	.256*	0,000
	Lower RayFace	-.509*	0,000
	Lower Proface	-.500*	0,000
	Mouth Einscan	.288*	0,000
	Mouth RayFace	-.416*	0,000
	Mouth Proface	-.480*	0,000
Middle Proface	Upper Einscan	.770*	0,000
	Upper RayFace	0,034	1,000
	Upper Proface	-.657*	0,001
	Middle Einscan	.710*	0,000
	Middle RayFace	.492*	0,000
	Lower Einscan	.748*	0,000
	Lower RayFace	-0,017	1,000
	Lower Proface	-0,008	1,000
	Mouth Einscan	.780*	0,000
	Mouth RayFace	0,077	1,000
	Mouth Proface	0,012	1,000
Lower Einscan	Upper Einscan	0,022	0,110
	Upper RayFace	-.714*	0,000
	Upper Proface	-1.405*	0,000
	Middle Einscan	-.038*	0,000
	Middle RayFace	-.256*	0,000
	Middle Proface	-.748*	0,000
	Lower RayFace	-.765*	0,000
	Lower Proface	-.756*	0,000
	Mouth Einscan	0,032	1,000
	Mouth RayFace	-.672*	0,000
	Mouth Proface	-.736*	0,000
Lower RayFace	Upper Einscan	.787*	0,000
	Upper RayFace	0,051	1,000
	Upper Proface	-.640*	0,013
	Middle Einscan	.727*	0,000
	Middle RayFace	.509*	0,000
	Middle Proface	0,017	1,000
	Lower Einscan	.765*	0,000
	Lower Proface	0,009	1,000
	Mouth Einscan	.797*	0,000
	Mouth RayFace	.094*	0,000
	Mouth Proface	0,029	1,000

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Table 4. Trueness familywise & pairwise comparisons.

Lower Proface	Upper Einscan	.778*	0,000
	Upper RayFace	0,042	1,000
	Upper Proface	-.649*	0,000
	Middle Einscan	.718*	0,000
	Middle RayFace	.500*	0,000
	Middle Proface	0,008	1,000
	Lower Einscan	.756*	0,000
	Lower RayFace	-0,009	1,000
	Mouth Einscan	.788*	0,000
	Mouth RayFace	0,084	1,000
	Mouth Proface	0,020	1,000
Mouth Einscan	Upper Einscan	-0,010	1,000
	Upper RayFace	-.746*	0,000
	Upper Proface	-1.437*	0,000
	Middle Einscan	-0,070	0,104
	Middle RayFace	-.288*	0,000
	Middle Proface	-.780*	0,000
	Lower Einscan	-0,032	1,000
	Lower RayFace	-.797*	0,000
	Lower Proface	-.788*	0,000
	Mouth RayFace	-.703*	0,000
	Mouth Proface	-.768*	0,000
Mouth RayFace	Upper Einscan	.693*	0,000
	Upper RayFace	-0,042	1,000
	Upper Proface	-.734*	0,006
	Middle Einscan	.634*	0,000
	Middle RayFace	.416*	0,000
	Middle Proface	-0,077	1,000
	Lower Einscan	.672*	0,000
	Lower RayFace	-.094*	0,000
	Lower Proface	-0,084	1,000
	Mouth Einscan	.703*	0,000
	Mouth Proface	-0,064	1,000
Mouth Proface	Upper Einscan	.758*	0,000
	Upper RayFace	0,022	1,000
	Upper Proface	-.670*	0,001
	Middle Einscan	.698*	0,000
	Middle RayFace	.480*	0,000
	Middle Proface	-0,012	1,000
	Lower Einscan	.736*	0,000
	Lower RayFace	-0,029	1,000
	Lower Proface	-0,020	1,000
	Mouth Einscan	.768*	0,000
	Mouth RayFace	0,064	1,000

mean error in accuracy of this laser scanner compared to two stereophotogrammetry systems was less than 2.00 mm with the exception of certain landmarks around the eyes.[19] In the *in vivo* study by Ayaz *et al* (2020) the mean error in accuracy for the Proface 3d Mid laser scanner was found to be 1.50 mm.[29] These values are in accordance to the mean facial scanning trueness results of this scanner in the present *in vitro* study (mean 1.30 mm) although not directly comparable. Regarding the RayFace, since it was only very recently introduced to the dental market (2021), there are no available studies in the literature looking into its scanning accuracy. Mean complete face scanning accuracy as reported by the manufacturer (personal communication) is 0.842 mm (SD 0.821 mm), whereas in the present study, mean complete facial scanning trueness was calculated to be 0.968 mm (SD 0.011).

In order to investigate the scanning trueness of the tested devices in the separate facial thirds, the mannequin head was divided into three horizontal subdivisions similar to the study by Zhao *et al* (2017).[21] The Einscan Pro HD scanner was again statistically significantly more true compared to both the RayFace and Proface 3D Mid scanners for all facial thirds. In the mouth area, in particular, the Einscan Pro HD deviated by 0.246 mm, statistically significantly less compared to the other two face scanners. Nevertheless, considering that the complete-arch intraoral scanning (IOS) accuracy threshold is below 0.10 mm,[30] none of the tested scanners, can be recommended for accurate extraoral scanning of the anterior dentition for digital smile design and restorative applications.This finding is in agreement with the study of Ortensi *et al* (2022). The authors reported significant distortion in frontal teeth dimensions when scanned directly with a stereophotogrammetry device.[31] Indeed, the RayFace scanner utilizes a facial scanbody workflow to overcome this limitation and accurately align the intraoral scan data to the facial scan data.

Regarding the performance of the structured light scanner in scanning the different facial thirds, the middle third was scanned with statistically significantly less trueness. Different studies have also reported lower accuracy for structured light scanners when scanning the middle third,[10] higher accuracy when scanning the upper third,[21,22] lower accuracy when scanning the upper third[32] or the lower facial third.[33] Direct comparison between these studies is not feasible because of fundamental differences in the study design, the use of inanimate subjects or real patients, the type of hand-held or stationery scanners used and the number and location of anthropometric landmarks evaluated.[1,24,33]

Regarding the performance of the stereophotogrammetry scanner in scanning the different facial thirds, RayFace scanned the middle third with statistically significantly higher trueness compared to both the upper and lower thirds almost by a factor of one half. According to the facial partition in the present study, the middle portion included relatively flat surfaces such as the left and right cheek areas and convex surfaces such as the nose that are easily picked up by the scanner. This can be attributed to the symmetric position of

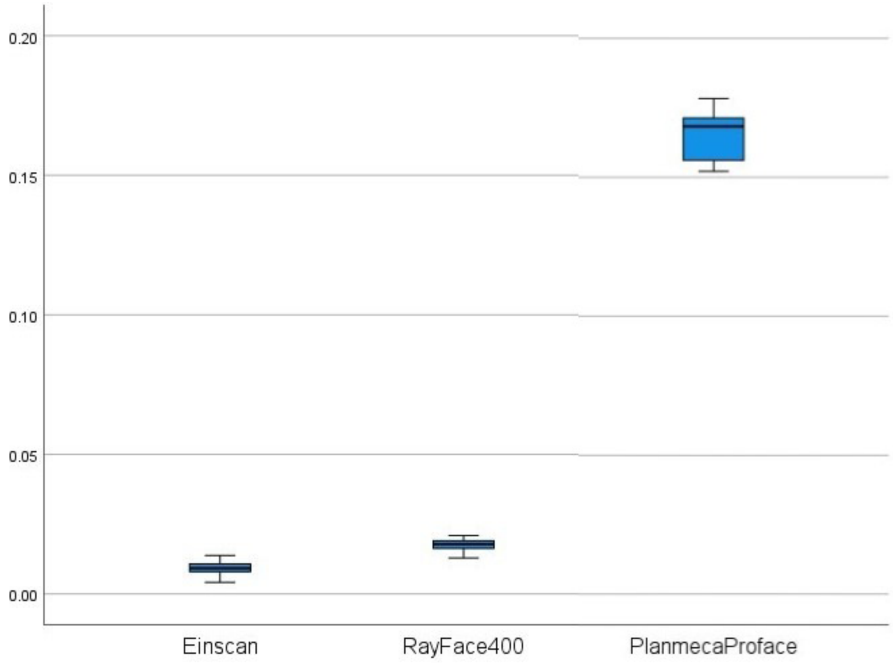

Figure 12: Complete face precision (mm).

the cameras on the arm rig. More accurate scanning of the middle third of the face has also been described in previous studies investigating the accuracy of the 3dMD scanner, which is considered to be the gold standard in the field of stereophotogrammetry.[21,24,34,35] On the contrary, in studies utilizing the Di3D stereophotogrammetry imaging system, scanning the middle third with lower accuracy has been described and attributed to the high error during the process of converting the 2D images of protruding areas such as the nose, chin and lips into 3D images inside the proprietary software.[25,36] As mentioned earlier, the RayFace scanner requires a facial scanbody (scout) workflow in order to embed the maxillary intraoral scan inside the facial scan data.[2] This process requires careful selection of identical landmarks between the face smile scan and the face scout scan data. According to the results in the present study, these landmarks should be selected in the middle third of the face for increased accuracy.

The Proface 3D Mid laser scanner scanned the upper facial third with statistically significantly less trueness compared to the middle and lower thirds. According to the facial partition in the present study, the upper third included both flat surfaces such as the forehead but also concave surfaces such as the eye sockets that have been shown to scan with lower accuracy using this particular laser scanner.[19,29] Due to limited viewing angles, laser scanners have been reported to struggle in areas of undercuts.[17] Amornvit and Sanokhan (2019) reported that the Proface 3D Mid laser scanner was unable to scan undercuts 6 mm wide in a depth of more than 2 mm.[18] The nasal areas have also been reported to scan with lower accuracy using a laser scanner[10] but this finding was not confirmed in the present study. Positioning of the mannequin head parallel to the horizontal plane and the angulation of the laser beam may have contributed to this.

Nine stainless steel spheres with a 4.00 mm diameter were firmly secured with cyanoacrylate adhesive in various positions on the mannequin face. Use of artificial facial markers has been described in the literature to aid in the accurate registration between the reference and test data sets.[33,37] Unfortunately, the spherical projections on the acquired 3D images by the stereophotogrammetry and laser imaging systems used in the present study were not clear as shown in Figure 5. Identifying the spheres on the textured images could have provided for a solution but the position of the measuring spheres on the textured 3D images would not always coincide with the position of the measuring spheres on the non-textured 3D images.[38] Therefore, a decision was made not to use the metal spheres as facial landmarks to aid in the registration of the meshes. In a recent study by Revilla-Leon *et al*, (2021), the authors compared the trueness and precision between the test and reference scans when the two meshes were aligned using either surface or landmark data.[39] They concluded that alignment procedures influenced the scanning accuracy of a stereophotogrammetry scanner. Alignment using surface to surface data produced higher trueness with the cheek areas being the most accurate whereas alignment using artificial landmarks produced higher precision with the forehead area being the most precise. Their findings are in agreement with the finding of the present study regarding the higher middle facial third trueness of the stereophotogrammetry device tested. Another study by da Silva Marques *et al* (2021) examined the accuracy of a laser scanner when the complete face, the complete face without the eyes and the lower third of the face were subsequently used for reference and test mesh alignment. They reported statistically significantly higher accuracy when the complete facial surface was used in alignment procedures.[40] Best-fit alignment algorithm using complete data

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sets as opposed to surface landmarks has also been shown to produce higher trueness and precision in *in-vitro* studies on both single teeth and complete arch alignment cases.[41,42]

In the present study, a thin layer of anti-reflex aerosol was sprayed onto the surface of the face including the metal spheres. Other *in vitro* studies that have used either stainless steel[18,39] or zirconia[38] facial markers have not used such an anti-reflex spray. Our purpose was to eliminate a possible glaring effect from the facial silicone and the metal spheres and focus on the effect that different anatomical convex and concave surfaces potentially have on facial scanning accuracy.

According to the facial scanner reliability classification by Mai and Lee (2020),[16] trueness results from the present study indicate that the Einscan Pro HD scanner can be classified as highly reliable for both the complete face scan and the separate facial thirds scans including the mouth area. The RayFace scanner can be classified as highly reliable for the complete face scan, the upper and middle facial third scans and the mouth area and reliable for the lower facial third scan. Finally, the Proface 3D Mid laser scanner can be classified as reliable for the complete face scan, the middle and lower facial thirds and mouth area and as moderately reliable for the upper facial third. Although statistically significant differences in accuracy among the three face scanners were detected, it is uncertain whether these differences bare clinical significance. The mean complete face trueness of all the scanners tested, with the exception of the Einscan Pro HD, fell within a 0.40 mm range and all scanners exhibited a deviation in complete face scanning trueness below the 2.00 mm clinical threshold.[15] The clinical accuracy threshold of the face scanners in relation to the field of application is another factor that has to be considered. Accurate extraoral scanning of the anterior dentition should be a prerequisite for restorative applications in oral rehabilitation cases.[31] Conversely, demand for accurate face scanning can be less strict in orthognathic, plastic and maxillofacial rehabilitation cases due to mobile tissues and muscle movements.[43] Future studies should investigate the effectiveness of different facial scanning modalities in capturing the anterior dentition and facial expressions during smile or speech accurately enough to allow the merging of the extraoral and intraoral data sets. Static and dynamic surface data acquisition sets could then be combined with tomographic data to produce the virtual patient and help streamline the rehabilitative workflows.

There are limitations to the present study. Using an inanimate mannequin head poses certain clinical restrictions. The even anti-reflex coating of the face with no facial hair and no skin or head movement may have contributed to higher accuracy results for the laser and structured light scanners.[34] Scanning the face using the Proface 3D Mid laser scanner took approximately 15 seconds whereas scanning with the Einscan Pro HD took approximately 60 seconds. A clinical implication of scanning a live patient instead of an inanimate subject with these devices is that it would probably lead to higher scanning times and lower accuracy compared to the results in the present study due to inadvertent head, eyes or facial skin movement. The stereophotogrammetry scanner on the other hand is less influenced by facial muscle movement as the scanning time is approximately 1 second.

CONCLUSIONS

Within the limitation of the present *in vitro* study, the following conclusions were drawn:

- The structured light scanner tested was statistically the more accurate face scanner for both the complete face and for all three different horizontal facial partitions.
- The structured light scanner was statistically the most accurate face scanner in the mouth area.
- All scanners tested had accuracy error levels below the 2.00mm acceptable threshold for extraoral scanning and therefore can be recommended for clinical use.

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