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Research article

Validation of three-dimensional facial imaging captured with smartphone-based photogrammetry application in comparison to stereophotogrammetry system

James Andrews [a,1], Abdulraheem Alwafi [b], Yashodhan M. Bichu [c], Benjamin T. Pliska [d], Nesrine Mostafa [d], Bingshuang Zou [d,*]

[a] *Graduate Orthodontics, Department of Oral Health Science, Faculty of Dentistry, University of British Columbia, Vancouver, Canada*
[b] *Faculty of Dentistry, Department of Dental Public Health, King Abdulaziz University, Jeddah, Saudi Arabia*
[c] *Private Practice, Abu Dhabi, United Arab Emirates*
[d] *Department of Oral Health Science, Faculty of Dentistry, University of British Columbia, Vancouver, Canada*

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ABSTRACT

Statement of problem: The development of facial scanners has improved capabilities to create three-dimensional (3D) virtual patients for accurate facial and smile analysis. However, most of these scanners are expensive, stationary and involve a significant clinical footprint. The use of the Apple iPhone and its integrated "TrueDepth" near-infrared (NIR) scanner combined with an image processing application (app) offers the potential to capture and analyze the unique 3D nature of the face; the accuracy and reliability of which are yet to be established for use in clinical dentistry.

Purpose: This study was designed to validate both the trueness and precision of the iPhone 11 Pro smartphone TrueDepth NIR scanner in conjunction with the Bellus3D Face app in capturing 3D facial images in a sample of adult participants in comparison to the conventional 3dMDface stereophotogrammetry system.

Material and methods: Twenty-nine adult participants were prospectively recruited. Eighteen soft tissue landmarks were marked on each participant's face before imaging. 3D facial images were captured using a 3dMDface system and the Apple iPhone TrueDepth NIR scanner combined with the Bellus3D Face app respectively. The best fit of each experimental model to the 3dMD scan was analyzed using Geomagic Control X software. The root mean square (RMS) was used to measure the "trueness" as the absolute deviation of each TrueDepth scan from the reference 3dMD image. Individual facial landmark deviations were also assessed to evaluate the reliability in different craniofacial regions. The "precision" of the smartphone was tested by taking 10 consecutive scans of the same subject and comparing those to the reference scan. Intra-observer and inter-observer reliabilities were assessed using the intra-class correlation coefficient (ICC).

Results: Relative to the 3dMDface system, the mean RMS difference of the iPhone/Bellus3D app was 0.86 ± 0.31 mm. 97% of all the landmarks were within 2 mm of error compared with the reference data. The ICC for intra-observer reproducibility or precision of the iPhone/Bellus3D app

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[*] Corresponding author. Department of Oral Health Science, Faculty of Dentistry, University of British Columbia 2199 Wesbrook Mall, Vancouver, BC, V6T 1Z3, Canada.

E-mail address: drzou@dentistry.ubc.ca (B. Zou).

[1] Now in Private Practice, Perth, Australia.

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was 0.96, which was classified as excellent. The ICC for inter-observer reliability was 0.84, which was classified as good.

Conclusions: These results suggest that 3D facial images acquired with this system, the iPhone TrueDepth NIR camera in conjunction with the Bellus3D Face app, are clinically accurate and reliable. Judicious use is advised in clinical situations that require high degrees of detail due to a lack of image resolution and a longer acquisition time. Generally, this system possesses the potential to serve as a practical alternative to conventional stereophotogrammetry systems for use in a clinical setting due to its accessibility and relative ease of use and further research is planned to appraise its updated clinical use.

1. Clinical implications

This new system, the iPhone TrueDepth NIR camera in conjunction with the Bellus3D Face app, was tested to demonstrate potential as an accurate and reliable method of capturing 3D facial imaging in adult patients without any craniofacial deformity. It can serve as a practical alternative to conventional stereophotogrammetry systems for use in a clinical setting and further research is planned to appraise other updated app/hardware combinations for clinical use.

Planning aesthetic dental treatment has encouraged the creation of a three-dimensional (3D) virtual patient, spurred facial smile analysis and simulation and digital smile design, allowed assessment of clinical outcomes and perhaps most importantly, enhanced coordinated clinician, patient and dental lab communication [1–3]. Conventional two-dimensional (2D) photogrammetric facial images can be highly erroneous due to deviations in lighting positioning, parallax, and focal length distances [4], and these are now being superseded by images acquired by 3D imaging technology, such as structured light scanning (SL), laser beam scanning (LB), near infra-red scanning (NIR), and stereophotogrammetry (SP) [5–10]. These imaging technologies can easily acquire 3D data and when combined with computer-aided design (CAD) software; create a model corresponding to the facial surface, from which surface measurements can be effectively analyzed.

Current 3D SP imaging devices, such as the 3dMDface system (3dMD) (3dMD Inc., Atlanta, GA), is a highly validated system that is accurate and reliable with its geometric accuracy claimed by the manufacturer of being less than 0.2 mm root mean square (RMS) [11,12]. 3dMD also possesses a significant advantage over SL or LB in that the SP capture technique is practically instantaneous (typical capture time, 1.5–2 ms), thereby minimizing error from motion artifacts [5,6]. Multiple studies have used it as the gold standard to compare newer 3D imaging technology [7,13] and test different portable scanning and SP technologies [14–16]. However, its disadvantages such as cost, lack of portability, bulky size, and overall large clinical footprint, have spurred the need to look for more cost-effective and portable 3D imaging technology alternatives.

The turn of the century sparked an ongoing digital and technological revolution in dentistry [17,18]. The advent of smartphones and ubiquitous internet connectivity that made round-the-clock access to computing at a fingertip possible has probably been the most disruptive technology of the 21st century. Smartphones and associated smartphone applications (apps) are now being utilized progressively in dentistry [19–26]. The “TrueDepth” camera system which uses near-infrared (NIR) as the light source was introduced in iPhone X (Apple Inc., Cupertino, CA) in 2017. The infrared sensors of this camera can capture light with a wavelength range of 800 nm–1300 nm to achieve a point cloud that can map complex shapes and is based on the same principle as structured light scanning. This system can be utilized with various applications to capture 3D facial images without the aid of an extra physical camera, such as Bellus3D Face Camera Pro (Bellus3D Inc., Campbell, CA), attached to the smartphone [19–23]. Rudy et al. compared the iPhone X scanner to a popular, portable 3D camera (Canfield Vectra H1, Canfield Scientific Inc., Parsippany, NJ) using the ScandyPro app (ScandyPro, New Orleans, LA) and obtained an RMS value of 0.35 mm, which is superior to the precision of other portable 3D scanners [24]. D’Ettorre et al. recently compared 3D facial scans obtained by 3dMD with two different applications, Bellus3D Face Application (Bellus3D Inc., Campbell, CA) and Capture (Standard Cyborg Inc., San Francisco, CA). The surface-to-surface deviation analysis results of their study showed a similar overlap percentage between the two apps, 80.01% ± 5.92% and 81.40% ± 9.59% within the range of 1 mm for Bellus3D and Capture, respectively [25]. Thurzo et al. evaluated the accuracy of Bellus3D Dental Pro app using Apple’s TrueDepth sensor compared to the corresponding facial surfaces segmented from cone-beam computed tomography (CBCT) imaging and they suggested limited applicability for clinical use due to some facial regions with differences greater than 3 mm [26]. However, the quantification of the mean difference between the iPhone scanner and the conventional gold standard system (3dMD) is yet to be ascertained.

This study was therefore designed to (1) evaluate the trueness of 3D craniofacial images of human subjects obtained using the TrueDepth camera of the Apple iPhone 11 Pro smartphone, combined with Bellus3D application and compare it to the industry gold standard, the 3dMDface stereophotogrammetry imaging system. In addition, this study also endeavored to (2) evaluate the intra-system precision of the “TrueDepth” camera, and (3) assess the inter-observer reliability of the post-processing analysis.

2. Material and methods

2.1. Study protocol

This prospective study was approved by the Institutional Research Board (Certificate number: H19-03203). The calculation of the power of this study was based on a previous study [24]. To detect a difference in the measurements of 0.44 mm with a standard deviation of 0.10 mm, a minimum of 21 subjects will be scanned with both methods to provide a power of 0.80 and α level of 0.05. The study sample involved 29 adults (6 males and 23 females) with an average age range of 25–50 years. All participants read and subsequently signed a written informed consent form. Subjects with facial hair or any craniofacial deformations were excluded from the study. Any facial makeup and jewelry were removed prior to the imaging procedure and any extraneous hair was retracted from the participant's face before the imaging.

2.2. Image acquisition protocol

Prior to the capture of the facial images using the two different 3D imaging systems (the reference data obtained from the 3dMDface system, and the measured data obtained from the Apple iPhone 11 Pro [IOS 14.0.1] TrueDepth NIR/Bellus3D app system), black liquid eyeliner was used to directly mark each participant's face representing 18 standard anthropometric surface landmarks (Fig. 1 and Table 1). The same investigator provided detailed instructions before each image capture. The participants sat upright on a chair with back support during the facial scanning procedures maintaining a closed mouth intercuspal position with closed relaxed lips.

Calibration was performed prior to each scan with the 3dMDface system using 3dMD acquisition software by holding the calibration board with dots and upside down "T" in a certain direction to allow image adjustment and alignment between the two modular units. The capture was completed in 2 ms with another 30 s needed to process and generate the final 3D model. Immediately after the imaging session with 3dMD, images were captured with the Apple iPhone 11 Pro in the same location utilizing a different protocol. The participant looked at the camera in a sitting position, and the position of the smartphone was adjusted and secured on a camera stand 30 cm away from the participant at an interpupillary height. The same neutral facial pose was established as applied to the 3dMD session. Image capture using the smartphone required the participant to slowly rotate their head to the left, back to the middle, to the right and then back to the middle, spanning about 14 s, following the manufacturers' instructions. Participants were instructed to practice the head movement three times prior to data capture to help obtain an eventual smooth image capture. The image acquisition protocol is illustrated in Fig. 2.

To maintain the conformity of lighting, no natural light was involved in the room, and LED front lighting for optimal facial lighting was utilized to prevent the occurrence of shadows. The images were collected in high definition as per the software settings in the Bellus3D application. Two examiners performed the calibration and the image acquisition together for each participant since the devices and the monitor were positioned relatively apart.

2.3. Assessment of accuracy

Alias Wavefront Object (.OBJ) format data files specific to the facial surface scans for each participant were uploaded for analysis into the Geomagic Control X (3D systems, Rock Hill, South Carolina, USA), a reverse engineering CAD software. After import, the 3D models were trimmed to remove the noise data, such as hair, ears, and submental soft tissue and establish the specific facial area of interest. The iterative closest point (ICP) algorithm of the software was utilized to align the data sets primarily. At this stage, the forehead and bridge of the nose were used as the surface area for registration [27] and subsequent deviation between the reference and the measured dataset and error analysis was carried out using the 'deviation analysis' function in the Geomagic Control X.

The 'trueness' component of accuracy in this study was thus analyzed by using both the surface-to-surface and point-to-point


[redacted]

Fig. 1. A 3D facial image with 18 pre-labelled landmarks.

Table 1
Facial landmarks definitions.

Order	Landmark	Abbreviation	Type	Definition
1	Trichion	tr	Midline	Midpoint of the hairline.
2	Nasion	n	Midline	The midpoint of the nasofrontal suture.
3	Pronasale	prn	Midline	The most protruded point of the nasal tip.
4	Subnasale	sn	Midline	The junction between the lower border of the nasal septum, the partition which divides the nostrils, and the cutaneous portion of the upper lip in the midline.
5	Sublabiale	sl	Midline	It is located on the skin below the vermillion
6	Menton	Me	Midline	It is located on the midline and is the lowest part of the chin
7, 8	Frontotemporale	ft	Bilateral	The most medial point on the temporal crest of the frontal bone.
9, 10	Zygion	zy	Bilateral	The most lateral point on the zygomatic bone.
11, 12	Alare	al	Bilateral	The most lateral point on the nasal ala.
13, 14	Crista philtri	cph	Bilateral	The point on the crest of the philtrum, the vertical groove in the median portion of the upper lip, just above the vermilion border.
15, 16	Gonion	go	Bilateral	The most lateral point at the angle of the mandible.
17, 18	Tragion	t	Bilateral	Located at the notch above the tragus of the ear, the cartilaginous projection in front of the external auditory canal, where the upper edge of the cartilage disappears into the skin of the face.

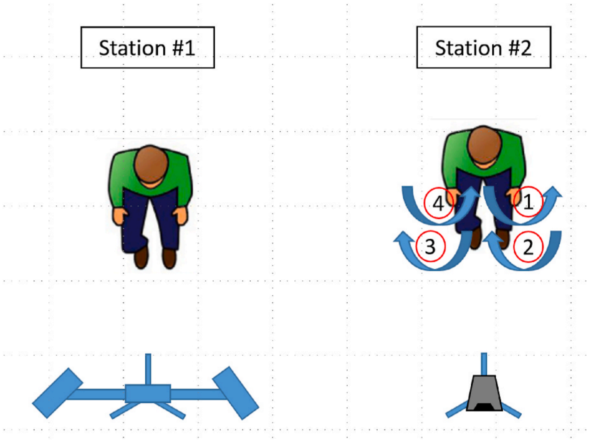

Fig. 2. Image acquisition protocol. Numbers and arrows indicate head turning order and direction. Station #1, with 3dMDface system, and station #2, with iPhone 11/Bellus3D app.

measures between the two registered surfaces. After registration, a color-coded heat map was generated with shades ranging from red to blue to represent visually the magnitude and direction of the differences between the two facial images (Fig. 3A and B). The root mean square (RMS) deviation was used to quantitatively record the magnitude of the difference between each pair of surfaces. This process was repeated for all 29 pairs of 3D facial scans. The mean global RMS value was calculated to quantify the trueness of each TrueDepth scan from the reference 3dMD image. The deviation between each pair of the 18 landmarks was also measured after registration. The tolerance range was set at a discrepancy of 1 mm, 1.5 mm, and 2 mm to highlight the limits of clinical consequence and to demonstrate which areas of the face data recorded, fell within this acceptable amount of clinical error. This tolerance range and the trueness of point-to-point measures were categorized into 4 groups according to the methodology of Aung and co-authors: (1) highly reliable if mean difference <1.0 mm, (2) reliable, 1.0–1.5 mm; (3) moderately reliable, 1.6–2.0 mm; (4) unreliable, >2.0 mm [28].

'Precision' was tested by comparing measurements between a reference image captured by the 3dMDface system and the facial scans consecutively obtained 10 times with a time-lapse of 2 min of a single participant captured by the TrueDepth camera system; statistically, represented by an intra-class correlation coefficient (ICC) calculation.

The final error estimated in post-processing with Geomagic software was also tested. An image subset of 10 randomly selected subjects was re-uploaded and processed by a second investigator, and the inter-rater reliability was measured with the ICC. The ICC was classified according to Koo and Li's study as follows: less than 0.5 as poor, values between 0.5 and 0.75 as moderate, values between 0.75 and 0.9 as good, and values greater than 0.90 as excellent reliability [29].

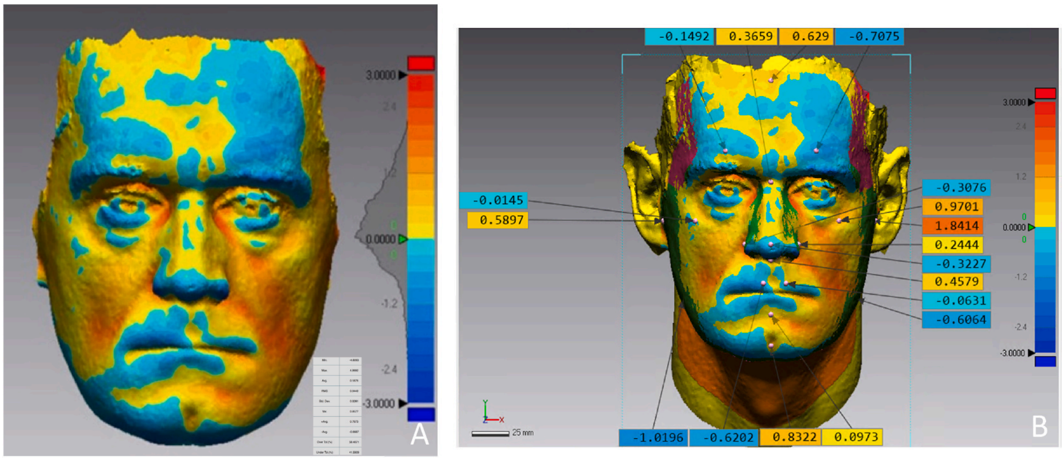

Fig. 3. Superimposition of the two scans and the color-coded heat maps generated with shades ranging from red to blue demonstrate A. Overall surface-to-surface facial analysis, and B. Individual landmarks with deviation values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Point-to-point deviations between two imaging systems (n = 29).

Facial landmarks	Mean/median difference	SD	*P value*	Confidence interval (lower; upper bound)/IQR	Count of deviances less than 1 mm	Count of deviances between 1.0 and 1.5 mm	Count of deviances between 1.6 and 2 mm	Count of deviances more than 2 mm
P1 Trichion[a]	0.07	0.40	0.025[b]**	−0.06; 0.07	26	3	–	–
P2 Nasion[a]	−0.02	0.27	0.239[b]	−0.21; 0.13	29	–	–	–
P3 Pronasale	−0.19	0.31	0.002**	−0.31; −0.07	29	–	–	–
P4 Subnasale	0.61	0.99	0.002**	0.22; 1.00	19	6	2	2
P5 Sublabiale	0.79	0.89	0.000***	0.47; 1.18	17	6	3	3
P6 Menton	−0.03	0.65	0.879	−0.29; 0.23	27	2	–	–
P7 Frontotemporale R	−0.19	0.33	0.002**	−0.32; −0.06	28	1	–	–
P8 Frontotemporale L	−0.24	0.35	0.002**	−0.38; −0.10	28	1	–	–
P9 Zygion R	−0.06	0.60	0.442	−0.30; 0.18	27	2	–	–
P10 Zygion L	0.31	0.72	0.027*	0.03; 0.60	24	4	1	–
P11 Alare R	−0.60	0.61	0.000***	−0.83; −0.35	26	3	–	–
P12 Alare L	−0.58	0.61	0.000***	−0.83;-0.34	25	3	1	–
P13 Cristaphilitri R	0.15	0.63	0.278	−0.10; 0.40	26	2	1	–
P14 Cristaphilitri L	0.21	0.66	0.076	−0.05; 0.47	25	3	1	–
P15 Gonion R	−0.85	1.13	0.002**	−1.41; −0.28	12	11	2	4
P16 Gonion L	−0.80	1.21	0.001**	−1.28; −0.32	16	5	3	5
P17Tragion R	0.25	0.93	0.119	−0.12; 0.62	20	7	–	2
P18 Tragion L	0.82	1.01	0.000***	0.42; 1.22	19	3	2	5

IQR, interquartile range, Q1; Q3.

*, P < .05; **, P < .01; ***, P < .001.

[a] non-normally distributed measures with Shapiro-Wilk test.

[b] Wilcoxon signed rank test results for non-normally distributed measures; otherwise one-sample *t*-test was used.

2.4. Statistical analysis

Statistical data analysis was performed by using SPSS statistical software program (version 24.0; IBM Corp, Chicago, Ill, USA). The Shapiro-Wilk test was used to evaluate the normality of the data distribution. For normal variables, mean and SD with a 95% confidence interval (CI) were used. If the variable was not normally distributed, median, and interquartile range (IQR, Q3-Q1) were used to report descriptive statistics. One-sample *t*-test and one-sample Wilcoxon Signed Rank test were used respectively to test if the deviations between the test and reference scans were significantly different. The ICC was used to evaluate the intra-rater and inter-rater reproducibility of the precision of the tested system and the post-processing with Geomagic software. P value $< .05$ was considered to be significantly significant.

3. Results

This study demonstrated a significant difference between the two imaging systems both with respect to their acquisition time as well as the technique utilized for imaging the participants. The 3dMDface system produced a practically instantaneous image, clocking only 2 ms for image capture, whereas the TrueDepth NIR camera on the Apple iPhone 11 Pro needed approximately 14 s. Further, iPhone-based imaging also required the participants to rotate their heads 180° left to right during the image acquisition process. Finally, mesh density (polygons/mm^2), which is dependent on the processing software, was found to be up to 1.5 million vertices per scan for the 3dMDface system.

The overall trueness of the iPhone TrueDepth camera/Bellus3D app system was analyzed for all participants as mean RMS surface-surface deviation, which was 0.86 ± 0.31 mm with a 95% CI of 0.75–0.98 mm and a P value less than 0.001. Among the 29 participants, 20 showed highly reliable results (RMS <1 mm), 8 had a reliable (RMS, 1.0–1.5 mm), and 1 had a moderately reliable result (RMS, 1.6–2.0 mm). None of the participants were found to demonstrate an unreliable registration result.

Table 2 demonstrates the point-to-point deviations between the two scan systems. The signed mean or median differences of all the 18 landmarks were found to be highly reliable (within ±1 mm), ranging from −0.85 to 0.83 mm with the smallest value of −0.02 mm in Nasion (the midpoint of the nasofrontal suture, $P > .05$), which also indicates to be the most accurate landmark with deviance <1 mm (highly reliable) in 29/29 of the subjects. Besides point Nasion, point Pronasle (the most protruded point of the nasal tip) also demonstrated a high accuracy with a deviation <1.0 mm for all 29 samples. Landmarks on the forehead, Frontotemporale R and L, in 28/29 subjects showed high accurate values and 1/29 as accurate value (deviation of 1.0–1.5 mm). Other landmarks on the midline, such as Menton (the lowest part of the chin, $P > .05$) and Trichion (the midpoint of the hairline), also showed reliable (2/29, 3/29) to highly reliable (27/29, 26/29) results. While midline points closer to the mouth and lips (Pronasale and Sublabiale, $P < .01$) showed less accurate results with 2/29 and 3/29 as unreliable, respectively. Other bilateral points demonstrating unreliable results were only found to be Gonion R&L and Tragion R&L with 4–5/29 and 2–5/29 samples having more than 2 mm deviance, respectively.

Participant-wise, on average, 15.9 (88%, range 12–18) of the 18 landmarks had deviations within the 1 mm range and on average, 0.5 (3%, range 0–3) of the 18 landmarks had deviations reported to be larger than a 2 mm range.

Fig. 4 demonstrates the deviations of surface-to-surface RMS and the 18 landmarks in 10 repetitively captured scans with iPhone TrueDepth NIR/Bellus3D system on the same subject. The intra-rater ICC, as a measure of the precision of the iPhone TrueDepth NIR

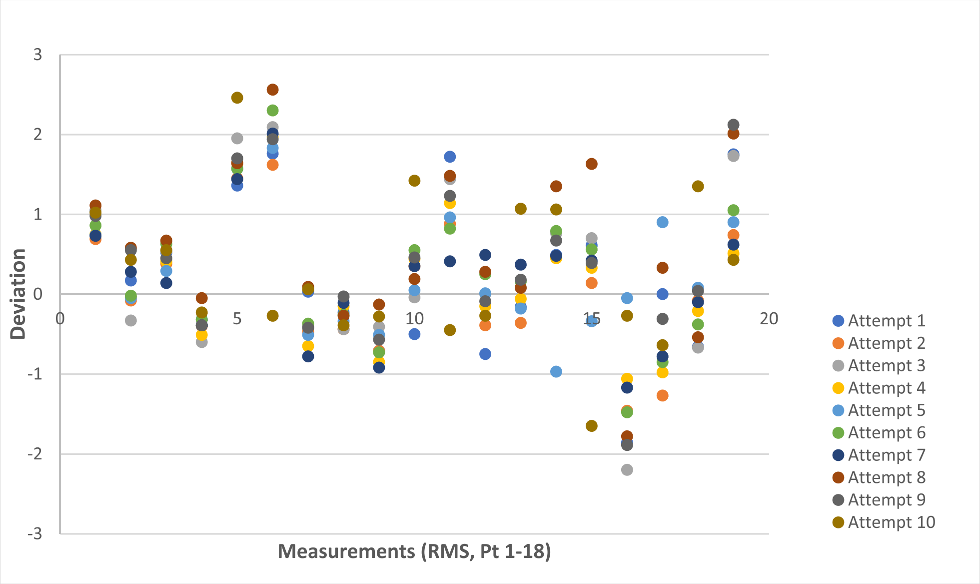

Fig. 4. The scatterplot of surface-to-surface RMS and 18 landmarks deviation in 10 repetitively captured images.

camera/Bellus3D app system, was calculated to be 0.96, classified as excellent reliable which demonstrated that the precision of this system is excellent. The reliability between the two investigators in post-processing with Geomagic tested with inter-rater ICC of 0.84, was classified as good. The Bland-Altman plot of the inter-rater differences also showed good reliability (Fig. 5).

4. Discussion

The utilization of advanced cameras inbuilt into contemporary smartphones combined with associated smartphone applications has enabled the creation of a virtual 3D or in some instances [30], even a virtual 4D patient [31]. However, whether this technological advancement can be achieved with accuracy and precision is yet to be concretely established and remains of clinical significance to both the patient and the healthcare provider. The robustness of these advances and their outputs would be vitally important to the diagnostic and treatment planning phases of patient management, especially for the objective assessment of facially orientated treatment planning.

The current study investigated the iPhone 11 TrueDepth NIR light-structured scanner combined with the Bellus3D app and demonstrated an RMS value of 0.86 mm, which is considered to be highly reliable [28]. Initial studies on facial scanning with smartphones [22,23] validated a physical camera which could be attached to the smartphone (such as the Bellus3D Face Camera Pro) as standalone hardware. In contrast, some of the recent studies have attempted to investigate the Apple iPhone X or Xs TrueDepth NIR light structured scanner combined with different apps, such as ScandyPro [24], Bellus3D Face or Capture app [25]. Rudy et al. [24] found that the iPhone X scanner had an RMS value of 0.35 mm following color map analysis, which indicates results superior to the ones obtained in the current study. A possible reason for this discrepancy could be the reference camera utilized in their study-a portable 3D device (Vectra H1) which had been priorly validated against the 3dMDface system, rather than a direct comparison with the industry gold standard, the 3dMDface system itself. Another explanation for the differing results could be the utilization of different apps by the two studies.

D'Ettorre et al. in a recent study [25], compared 3D facial scans obtained by stereophotogrammetry with two different apps supporting the TrueDepth system of iPhone Xs and found that facial image acquisition with the new smartphone applications along with the TrueDepth sensors shows promising clinical results; findings which are generally in conformity with the results of this study. However, this study did not provide the exact value of RMS for the tested system, which has been calculated in the current study.

It is vitally important to establish what constitutes an acceptable clinical error in the acquisition of facial scan data when discussing the study results. However, no formal guidelines have been proposed with regard to a threshold of accuracy for a 3D data acquisition system to be used clinically. Thurzo et al. suggested that 3 mm or more of the deviation should be clinically relevant [26]. Fourie et al. proposed the mean absolute error of more than 1.5 mm as clinically significant [32]. D'Ettorre et al. considered this range to be of 1 mm [25], and multiple studies conducted previously, utilized errors less than 2 mm to be appropriate for accuracy and precision [5,6,8,14]. In the current study, we applied Aung et al.'s [28] recommendations that deviations from the reference face scan can be divided into four groups; those with a deviation between 0 and 1 mm were depicted as highly reliable, between 1 and 1.5 mm as reliable, between 1.5 mm and 2 mm as moderately reliable and greater than 2 mm as unreliable. This classification of the range will provide clinicians and researchers with detailed information and allow them to choose an appropriate 3D scanner based on their specific need, especially when highly precise measurements are required, such as for cleft lip and nose surgery or other pediatric facial measurements [27].

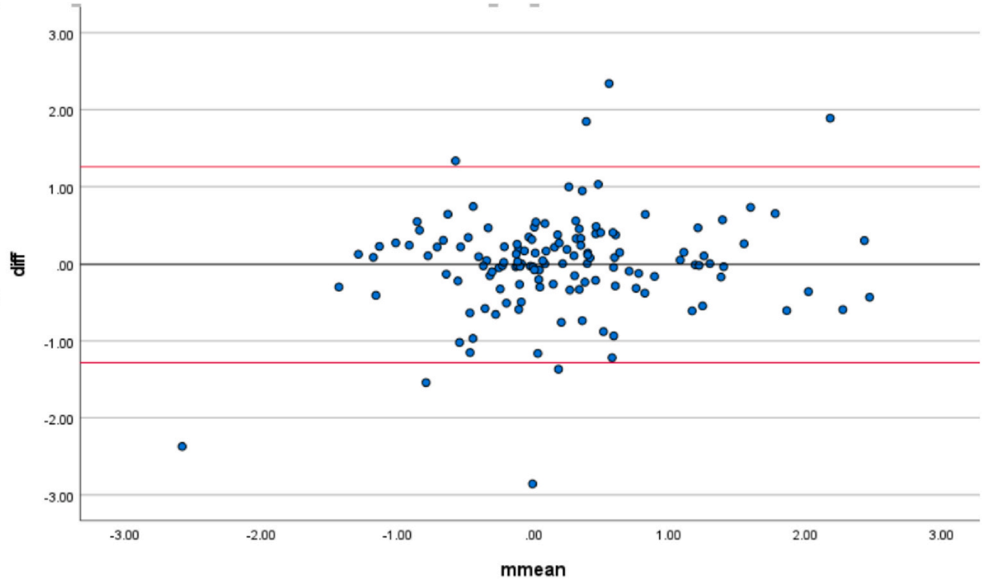

Fig. 5. Bland-Altman plot of inter-rater reliability in post-progressing with Geomagic software.

The first objective of this study was to investigate the trueness of the iPhone TrueDepth system, for which the mean RMS error was utilized as the measure of global? Surface-to-surface accuracy. For all participants in this study, this value was noted to be 0.86 ± 0.31 mm different from the 3dMDface system, and this is comparable to the previous studies of the hand-held Bellus3D Face Camera Pro (mean RMS error 0.91 ± 0.32 mm) [23] and Vectra H1 devices (0.84 mm) [14]. While Liu et al. [22] found smaller mean absolute differences between Bellus3D and direct measurement (0.61 ± 0.47 mm) and between Bellus3D and 3dMD (0.38 ± 0.37 mm), respectively. A possible reason for this discrepancy could be the use of a mannequin head in their study instead of human participants, where minor changes in facial movement or expression are unavoidable and constitute a major source of errors and artifacts [24,25]. Another reason for this discrepancy could be the longer capturing time compared with the gold standard (3dMDface system). In the present study, even though the primary operator was experienced and well-trained in the use of the facial scanning system, completion of the TrueDepth NIR facial scans consumed 14 s, while it takes 2 ms to complete the same facial scan with the 3dMDface system. Furthermore, the rotation of the participant's head during image capture with the Bellus3D app can further cause an increase in the capture error. In an experimental setting that this study and previous studies have set up, the trueness of portable devices and/or combined apps tested is clinically acceptable and showed good reliability (deviation <2 mm). But their reliability may be questionable, if these devices are to be used in a more generalized clinical situation, especially for younger children, or patients with difficulties in following instructions, as well as in patients with facial hair or craniofacial deformities.

When examining specific areas of the face, it is possible to identify structures that stand out as less accurate regions for data acquisition, since the human face exhibits unique curvature and moveable soft tissue areas. It is, therefore, possible that a face scanner may possess a good overall accuracy, may exhibit limited local accuracy in these specific areas, and this may be of clinical significance. This study examined 18 individual anatomic landmarks in the craniofacial region and revealed an increased deviation in the face for structures furthest from the facial midline areas. The bilateral points, which included soft tissue Gonion and Tragion, showed the greatest number of points outside the 2 mm deviation limit, and this may be related to the stretching of soft tissues caused by the movement of the head during the image capture [24]. The only landmarks in the midline that showed poor reliability are Subnasale and Sublabiale, which may have resulted due to the mobility of the upper lip or perioral muscles and is in agreement with a previous study that also found that the less accurate areas are those rich in curvatures, such as the mouth and lips [25].

The region of the face (the forehead and nasal bridge) that was used for the superimposition in this study is located towards the upper third of the face, and this specific facial area has been established as a relatively stable facial surface area [33], and the authors of the present study contend that this would allow better assessment of the middle and lower parts of the face, which are more likely to be affected by surgical, prosthetic and orthodontic treatments. This study is also in agreement with previous studies which mention that this method could be used in future studies primarily when looking at facially orientated treatments or assessing facial growth [34].

In order to validate the precision or reliability of the imaging system, this study also involved the capture of ten single images of the same subject and the utilization of the ICC; and study results demonstrate that the measure of reliability was 0.96, which was classified as excellent. Furthermore, since we pre-marked 18 landmarks on each subject's face, this procedure helped decrease the errors involved in the point-to-point comparison [14,15].

5. Limitations

One of the limitations of this study is the inability to include and evaluate patients with facial hair since it has been established that facial hair is not conducive to accurate soft tissue imaging [35]. Further, the relatively large mesh size (polygons/mm^2) generated by the iPhone hardware and Bellus3D software, claim to capture 250,000 to 500,000 vertices per scan, is another limitation of this study, as it does not accurately define areas of shape complexity and noticeable curvature in high detail, such as the nose and the lips. However, it was effective when depicting less complex shape areas of the face such as head shape, cheek, and chin contour. The results of this study indicate that this present technology would not be suitable for merging intra oral scans with facial scans to create the virtual 3D patient as suggested by another study discussing digital smile design [3]. However, higher resolution cameras combined with improved hardware and software resolution may provide this exciting and valuable capability [19,30].

It is worth mentioning that although few pilot studies, including the current one, endeavored to incorporate the Bellus3D app and smartphones to generate 3D facial images; the manufacturer decided to wind down the Bellus3D app itself by the end of 2022. Subsequently, this app is no longer available for download from the App store. Therefore, despite the majority of the pilot studies demonstrating relatively promising results, the clinical applicability of these studies is limited due to the commercial unavailability of this particular app. However, with continued technological advancements, similar and possibly, more user-friendly, and accurate face apps such as ScandyPro [24], Capture [25], or Face2Gene [26], coupled with cost-effective hardware options could enable the further development of alternatives to conventional stereophotogrammetry systems. Furthermore, validation methods, such as the current one, will undoubtedly help shed light on expanding the clinical applicability of these alternative systems.

6. Conclusions

1. TrueDepth NIR camera of iPhone 11 with the Bellus3D app system can capture 3D facial images with an acceptable level of accuracy when compared to the 3dMDface system.
2. The precision value of this system was shown to be excellent, which demonstrated that the 3D images produced by the iPhone TrueDepth scanner showed high repeatability.

3. TrueDepth camera combined with the Bellus3D app can be considered as a less expensive, portable, and clinically acceptable alternative to the conventional sterrophotogrammetry 3dMDface system for 3D facial image acquisition and subsequent diagnosis and treatment planning in a clinical setting.

Credit author statement

James Andrews: conceived the experiments; performed the experiments; analyze the data; wrote the paper. Abdulraheem Alwafi: performed the experiments. Yashodhan M. Bichu: interpreted the data, wrote the paper. Benjamin T. Pliska: conceived and design the experiments. Nesrine Mostafa: conceived and design the experiments. Bingshuang Zou: conceived and design the experiments; analyzed and interpreted the data; wrote the paper.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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