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Accuracy of three-dimensional optical devices for facial soft-tissue measurement in clinical practice of stomatology

A PRISMA systematic review

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Abstract

Background: The accuracy of 3-dimensional (3D) optical devices for facial soft-tissue measurement is essential to the success of clinical treatment in stomatology. The aim of the present systematic review was to summarize the accuracy of 3D optical devices used for facial soft-tissue assessment in stomatology.

Methods: An extensive systematic literature search was performed in the PubMed/MEDLINE, Embase, Scopus and Cochrane Library databases for studies published in the English language up to May 2022 in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines. Peer-reviewed journal articles evaluating the facial soft-tissue morphology by 3D optical devices were included. The risk of bias was performed using the Quality Assessment Tool for Diagnostic Accuracy Studies-2 guidelines by the 2 reviewers. The potential publication bias was analyzed using the Review Manager software.

Results: The query returned 1853 results. A total of 38 studies were included in this review. Articles were categorized based on the principle of devices: laser-based scanning, structured-light scanning, stereophotogrammetry and red, green, blue-depth camera.

Conclusion: Overall, the 3D optical devices demonstrated excellent accuracy and reliability for facial soft-tissue measurement in stomatology. red, green, blue-depth camera can collect accurate static and dynamic 3D facial scans with low cost and high measurement accuracy. Practical needs and availability of resources should be considered when these devices are used in clinical settings.

Abbreviations: 2D = two-dimensional, 3D = 3-dimensional, CBCT = cone beam compute tomography, CT = compute tomography, MRI = magnetic resonance imaging, RGB-D = red, green, blue-depth.

Keywords: accuracy, facial soft-tissue measurement, systematic review, three-dimensional optical devices

1. Introduction

The quantitative measurement of facial size and shape plays a key role in clinical practice of stomatology, including oral and maxillofacial surgery, orthodontics and prosthodontics, to assist practitioners in preoperative diagnosis, surgery planning, fabrication of prostheses and postoperative evaluation.[1–3] Accurate acquisition of facial soft-tissue morphology significantly contributes to enhancing the reliability of treatment planning and monitoring the results of surgical and restorative procedures.[4,5] In the past, facial anthropometry was performed using calipers, steel tapes and protractors to fabricate facial morphology.[6] However, due to the complex 3-dimensional (3D) anatomy, dynamic movement and variability of human face, it is a challenge to quantitatively assess and measure facial morphology and function in an accurate and efficient way.

Two-dimensional (2D) measurement is a basic approach applied to analysis of maxillofacial morphological features by measuring the corresponding distance and angle on digital photographs taken from different angles.[2,3,7] However, this conventional method cannot accurately assess the complexity of 3D soft-tissue facial anatomy, for the reasons that it is relatively hard to appropriately evaluate the geodesic distance or volume

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The medical ethics committee approval was not required in this study since no human or animal subjects were involved.

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of facial portions.[8] As a consequence, the prediction of results and prognosis of treatments can be limited in this method. With the application of digital technology in stomatology, advanced instruments, including compute tomography (CT), cone beam compute tomography (CBCT) and magnetic resonance imaging (MRI), have been applied to the reconstruction of facial soft-tissue morphology.[9] However, due to the limitation of image pixel resolution and the exposure of radiation, these methods are not appropriate for the measurement of facial soft-tissue morphology.

Since laser scanner was invested in 1985, 3D optical devices which provide 3D replication of the facial structure with high accuracy and good safety have gradually been applied, not only for research and educational fields, but also for the clinical environment.[10,11] These devices can obtain 3D face model with real skin texture and color in open data format through noncontact measurement in a short period, which is considered to be a more suitable option for quantification of volume and contour of facial soft-tissue measurement.[12] Furthermore, the obtained 3D images can be digitally archived, which helps rapid longitudinal assessments, researches and communication in clinical practice.[13,14]

Because the accuracy of the 3D optical devices is quite important for its application, many studies have investigated the reliability of these devices, but few studies systematically analyzed their accuracy based on their working principle.[15–19] Furthermore, it appears that no investigation has systematically summarized their reliability and incorporated these devices into clinical practice of stomatology. Therefore, the aim of the present systematic review was to summarize the current evidence, including working principles, characteristics and accuracy of 3D optical devices for facial soft-tissue measurement among living subjects, with a special focus on their application in the clinical practice of stomatology.

2. Method

The present systematic review was performed in accordance with Preferred Reporting Items for Systematic Reviews and Meta-analyses statement and registered in the PROSPERO database under registration number CRD42022331939.[20] The medical ethics committee approval was not required in this study since no human or animal subjects were involved.

The guiding research question for this study was "When assessing facial soft-tissue morphology in clinical practice, which are the most reliable 3D optical devices in terms of accuracy?." According to the population, intervention, comparison, and outcome scheme, the population included people who received digital facial impression. The intervention group consisted of face models obtained by 3D optical devices. The comparison group consisted of human faces obtained by conventional anthropometry and other optical devices. The outcome was the accuracy of facial anthropometric measurements.

2.1. Search strategy

An extensive search in the electronic databases of the PubMed/MEDLINE, Embase, Scopus and Cochrane Library for articles published up to May 2022 was performed to identify suitable publications. The keywords used were: (face OR facial) AND (3D OR 3-dimensional OR 3 dimensional) AND (optical scanner OR structured light OR 3D scanner OR laser scanner OR white-light scanner OR stereophotography OR photogrammetry) AND (validation OR accuracy OR repeatability OR precision OR agreement OR concordance OR reproducibility OR reliability OR comparison OR trueness OR feasibility).

2.2. Inclusion and exclusion criteria

Publications that fulfilled the following inclusion criteria were selected: research studies, clinical studies, randomized and non-randomized controlled trials, case-control studies, cohort studies, and cross-sectional studies that were performed on living subjects; quantitative assessments of metric measurements of anthropometric features of face obtained by 3D optical devices; articles published in English.

The following exclusion criteria were applied: conference papers, reviews, case reports, case series, congress abstracts, author or editorial opinion articles; studies performed with devices other than 3D optical instrument; studies in which the reliability of facial measurements could not be quantitatively determined; studies written in languages other than English.

2.3. Study selection and data collection process

The relevant information from the articles retrieved by each search strategy were unified and duplicate entries were removed. For study selection, 2 investigators evaluated the titles and abstracts separately. Those considered ineligible by both reviewers were excluded outright, while those considered ineligible by 1 reviewer but eligible by the other were retained for full-text reading. All studies not excluded were read in full-text by 2 investigators working together, who then selected those that fully met the eligibility criteria and performed data extraction. Any disagreement was resolved by discussion and consensus among all authors.

The following data were extracted from the eligible studies: author, year of publication, participant information, the type of 3D optical device, scanning methods, reference standard for validation, number of landmarks used, number of measurements, and major findings including results and conclusions.

2.4. Quality assessment/risk of bias

The risk of bias was performed using the Quality Assessment Tool for Diagnostic Accuracy Studies-2 guidelines by the 2 reviewers.[21] This tool includes questions related to 4 bias domains, including patient selection, index test, reference standard, and flow and timing. When 1 or more of the key domains were scored as high risk, the study in question was judged as showing a high risk of bias in its overall judgment. When more than 2 key domains were rated as unclear, the study was regarded as having an unclear risk of bias.

3. Results

3.1. Study selection

The database search retrieved 1853 references: 665 from PubMed/MEDLINE, 739 from Scopus, 426 from Embase and 23 from the Cochrane Library. After removing duplicates, 1341 studies remained. Of these, 1248 were excluded after analysis of titles and abstracts. After reading full texts, 55 studies were excluded for failure to meet the eligibility criteria. At last, 38 studies remaining in the qualitative analysis and quantitative analysis. The results of the searching and screening process are summarized in Figure 1.

3.2. Quality assessment and applicability concern

The quality assessment results from the Quality Assessment Tool for Diagnostic Accuracy Studies-2 showed that among the 38 articles included, 33 studies had a low risk of bias, 4 studies had a high risk of bias and 1 study displayed unclear risk of bias. For applicability, 31 studies showed a low level of concern, 3 studies demonstrated an unclear level of concern, and 4 studies showed a high level of concern (Fig. 2).

3.3. Study characteristics

Studies were categorized according to working principles of the 3D optical devices being tested: laser-based scanning, structured-light scanning, stereophotogrammetry and red, green,

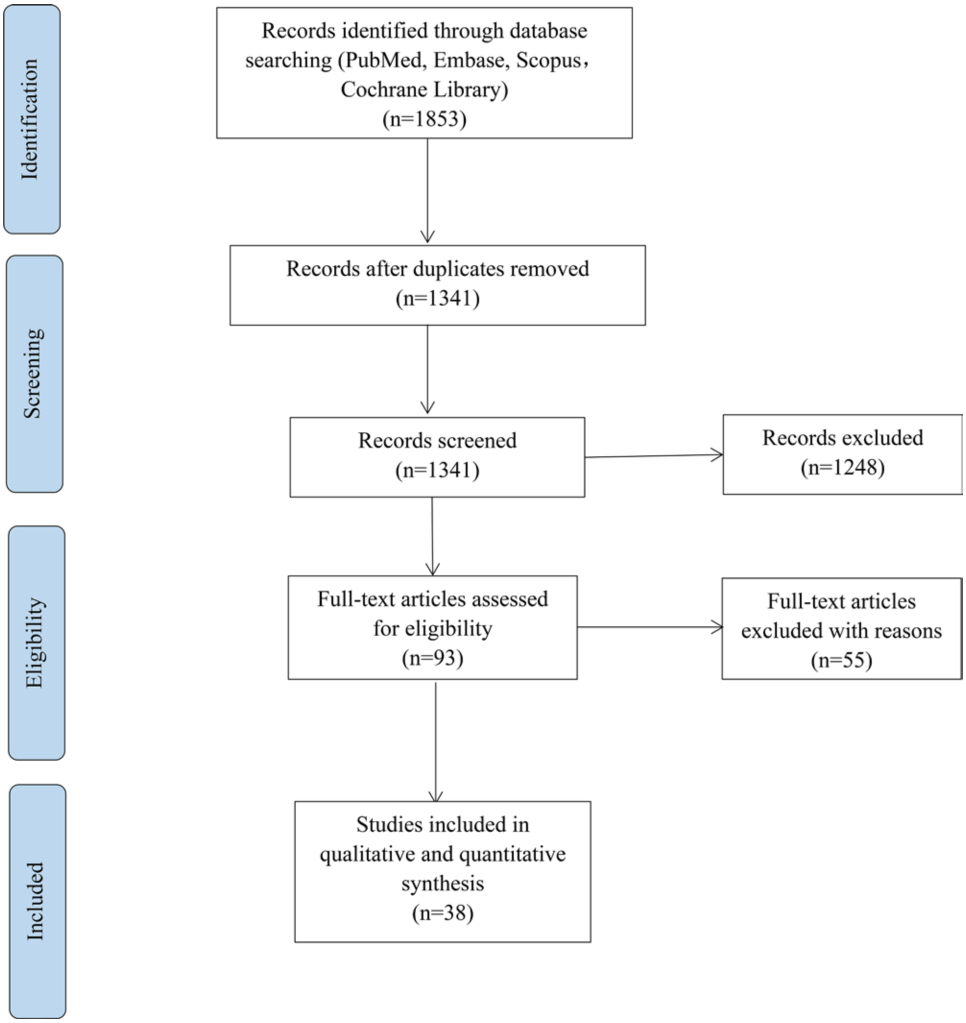

Figure 1. Flow chart of the literature search and results.

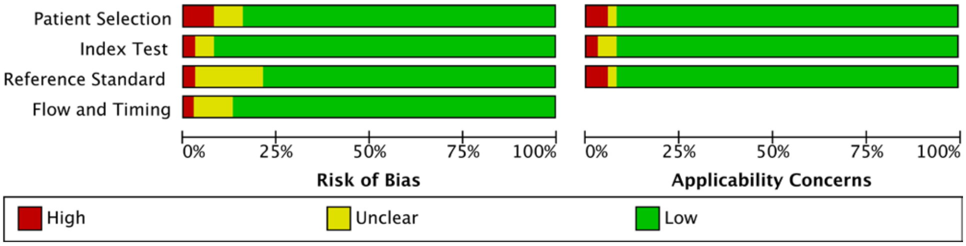

Figure 2. Risk of bias and application.

blue-depth (RGB-D) sensors. The reference methods included all kinds of principles, with the largest number of articles using direct anthropometry. Regarding to the test methods, all relevant categories were included, most of the studies tested stereophotogrammetry devices and 8 studies used 2 or 3 different optical devices. Table 1 organized the extracted data according to the characteristics of the studies summarized the main outcomes of them, including the major findings.

3.3.1. Laser-based scanning. The laser-based scanning technique functions by projecting the laser beam across the object to generate characteristic light fringes and using a digital camera with a charge-coupled device to obtain the digital image signal of the measured object, which can quickly acquire 3D point clouds without texture and convert into a triangular model in the software. Combined with the regional images, the x, y, and z coordinates of the surface points were determined and a 3D image which can be rotated in any direction was generated.[12,53]

Eleven published studies tested fixed or handheld laser scanner in living subjects; direct anthropometry was the most commonly used reference method, stereophotogrammetry, CT and 2D photogrammetry were also used. Laser-based scanning technology was used as a reference method in 2 studies.[3] Laser-based scanning technique has the advantages of good scanning flexibility, fast imaging speed, wide application range and harmless to human body. Currently, Minolta Vivid from Minolta Company in Japan is the most common laser scanner used in the clinical practice of stomatology. By comparing the data collected from volunteers and mannequin with laser scanners, Gibelli et

Table 1

Characteristics of the included studies.

Study	No. Participant	Scanner	TM	RF	No. LM	Measurements	Results and Conclusions
Akan et al[22] 2021	26	iPhone X	RGB-D	SP	23	7 liner distances; 3 angles	RMS values were found between 0.58 and 1; images of a smart-phone can be used to record and evaluate 3D soft tissue changes.
Anas et al[23] 2019	150	Creaform®	LS	2D	22	13 liner distances	Measurements taken with laser scanner were higher relative to the 1 taken by camera. The mean differences between the 3D and the 2D methods of quantifying facial morphology indicated a statistically significant positive difference.
Aung et al[24] 1995	30	NR	LS	DA	41	83 liner distances	12 showed a mean difference less than 1.0 mm and 16 with less than 1.5 mm difference. LS can be useful in selected anatomical parts of face.
Ayaz et al[25] 2020	50	ProMax® 3D Mid; Vectra® H1	LS; SP	DA	22	7 liner distances; 17 angles	SP performed better than LS, with borderline significance. SP was found to a reliable and accurate tool for morphological evaluation of soft tissue in comparison to 2D imaging and laser scanning.
Aynechi et al[26] 2010	10	3dMDface	SP	DA	19	18 liner distances	Mean measurements derived from 3D images and DA measurements were mostly similar. 3dMDface system demonstrated a high level of precision, especially when facial landmarks were labeled.
Bakirman et al[27] 2017	2	NR	low-cost SL	SL	3D point clouds	surface-to-surface distance maps	RMSD errors between the reference and the tested facial reconstructions < 1 mm; absolute mean difference 0.4 to 0.8 mm. Both tested systems can be used for 3D face modeling; motion artifacts should be considered.
Camison et al[28] 2018	26	Vectra H1	SP	SP	17	136 linear distances; 26 surface-to-surface distance maps	The distances were highly comparable with an average TEM value of 0.84 mm (0.19–1.54 mm). The average RMS value of the surface-to-surface comparisons was 0.43 mm (0.33–0.59 mm). The portable device is highly repeatable, reliable and accurate. It can be used in the clinical setting but motion artifacts should be considered
Dindaroglu et al[29] 2015	80	3dMDflex	SP	DA	11	10 liner distances; 6 angles	Very high level of agreement between the methods. The system is reliable and accurate; errors < 2 mm; validated for practical purposes.
Duppe et al[30] 2018	14	3dMDtrio	SP	DA	20	14 liner distances	The reliability of the digital and direct methods varied greatly depending on the 14 anthropometric distances. The digital and direct methods were generally compatible in reliability and agreement.
Ettorre et al[31] 2022	40	iPhone Xs (Bellus3D or Capture application)	RGB-D	SP	18	surface-to-surface distance maps	Deviation between Bellus3D and 3dMD showed an overlap percentage of 80.01%±5.92% and 56.62% ±7.65% within ranges of 1 mm and 0.5 mm discrepancy. Images from Capture showed an overlap percentage of 81.40% ± 9.59% and 56.45% ± 11.62% within ranges of 1 mm and 0.5 mm.
Germec-Cakan et al[12] 2010	15	3ShapeR250; ZScanner700; 3dMDface	LS; Portable LS; SP	DA	15	11 liner distances	Significant differences among the 4 methods but SP was the most promising method.
Ghoddousi et al[33] 2007	6	NR	SP	DA	14	15 liner distances	The tested device is sufficiently accurate and reliable for clinical use, the mean difference was 0.23 mm (shortest distance) and 0.13 mm (surface).
Gibelli et al[33] 2018	50	Sense®	LS	SP	50	14 liner distances; 12angles; point- to-point distances	On average, RMS point-to-point distances were 0.65 mm (inter-devices) and 0.42 mm (intra-device); the low-cost laser scan device does not meet the standards for 3D facial acquisition on living persons.
Gibelli et al[34] 2018	50	VECTRA H1	SP	SP	50	15 liner distances; 12 angles; 3 surface areas; 3 volumes	Most linear, angular, and surface area measurements had high repeatability in M3 versus M3, H1 versus H1, and M3 versus H1 comparisons (range, 82.2%–98.7%; TEM range, 0.3–2.0 mm; rTEM range, 0.2–3.1%). Volume measurements and RMSD in living subjects are more affected by involuntary motion and should be considered with caution.
Gomes et al[35] 2019	15	Artec Eva	SL	DA	14	11 liner distances	The scanner showed excellent reliability in all measures. Measurements accuracy with scanner was around 2 mm when the points were not previously marked and about 1 mm when the points were marked.
Incrapera et al[36] 2010	34	3dMD	SP	CR	5	10 liner distances	The mean differences of the soft tissue landmarks were found to range between 1.06 and 8.07 mm and 1.26 and 7.34 mm for lateral cephalometric and 3D readings, respectively.
Joe et al[37] 2012	9	Konica-Minolta Vivid 9i	Fixed LS	DA	14	10 linear distances	The digital system is a valid method with results as precise as DA and accurate (only 3 distances differed > 3 mm).
Kau et al[38] 2006	38	Minolta Vivid 900	Fixed LS	LS	3D point clouds	surface-to-surface distance maps	The mean shell deviation in superimposition of whole faces was 0.37 ± 0.07 mm for males and 0.35 ± 0.09 mm for females, as shown by scans taken within 1 week. The 3D images may be used as accurate representations of facial morphology within the errors reported.

(*Continued*)

Table 2

(*Continued*)

Study	No. Participant	Scanner	TM	RF	No. LM	Measurements	Results and Conclusions
Kim et al[39] 2015	30	Morpheus 3D®	SL	DA	21	16 liner distances	The average value of differences for all variables was 0.75 mm. Precision was high in both methods, with error magnitudes under 0.5 mm.
Kim et al[9] 2018	40	Morpheus Co	LS	CT	10	9 liner distances;5 angles	The gonial angle measured between tragion'-gonion'-menton' using a 3D facial laser scan was comparable with values from 3D CT scan.
Kim et al[40] 2018	5	Vectra M3; Vectra H1	SP	DA	29	25 liner distances	The handheld and conventional camera methods yielded larger measurements than direct calipers. The 3D handheld camera showed high accuracy and reliability in comparison with traditional models.
Knoops et al[18] 2017	8	M4D Scan; Structure Sensor	SL	SP	3D point clouds	surface-to-surface distance maps	Relative to the 3dMDface System, accuracy for M4D Scan (90% within 2 mm; RMS of 0.71 mm ± 0.28 mm) and Structure Sensor (80%; 1.33 mm ± 0.46) were high. M4D Scan and Structure Sensor precision were 0.50 ± 0.04 mm and 0.51 ± 0.03 mm, respectively.
Kovacs et al[41] 2006	6	Minolta Vivid 910	Fixed LS	DA	48	>680 linear distances and angles	On a subset of 560 distances: mean difference 1.32 mm, SD 5.67; >50% of the variables do not satisfy the reliability tolerance threshold for practical applications (>2 mm).
Lippold et al[42] 2014	15	FastScan	Handheld LS	DA	12	7 liner distances	Most of the distances differ < 1 mm from the reference standard. The system is validated and clinically useful due to its high inter-method agreement except for mouth width and nasion–subnasale distance. The quality of the scan can be improved.
Maue´s et al[1] 2018	10	Microsoft Kinect	RGB-D	SP	3D point clouds	10 regions of interest;7 liner distance	The average difference between the 2 methods was 0.3 ± 2.03 mm. Reproducibility showed an average difference between the images taken with Kinect of 0.1 ± 0.6 mm. Kinect showed good precision and accuracy.
Nightingale et al[43] 2020	20	iPhone® 8S	RGB-D	SL	3D point clouds	surface deviation	The smartphone-based photogrammetry produced scans with 1.3 mm (±0.3 mm) accuracy in comparison to a metrology-rated gold standard device and were 88% (±14%) complete.
Park et al[44] 2012	20	Di3D	SP	DA	7	5 liner distances	Mean difference 0.73 mm; range 0.13–1.53 mm. No significant differences between the 2 methods. The device is sufficiently accurate and reliable for clinical use (error < 1 mm).
Piedra-Cascón et al[19] 2020	10	Face Camera Pro Bellus	SL	DA	6	5 liner distances	The mean value of the manual and digital group discrepancy was 0.91 ± 0.32 mm. The dual-structured light facial scanner tested obtained a trueness mean value of 0.91 mm and a precision mean value of 0.32 mm.
Raffone et al[45] 2021	10	iPad Pro (3rd generation)	RGB-D	DA	17	23 liner distances	The comparison between manual and digital measurements showed a mean difference of 0.95 ± 0.25 for Free technique and 1.00 ± 0.29 for the Slider technique. Accuracy of low-cost portable scanner can be suitable for clinical use.
Rudy et al[46] 2021	16	iPhone X	RGB-D	SP	10	color map; surface distance	Average RMS was 0.44 mm following color map analysis and 0.46 mm for surface distance between anatomical landmarks.
Savoldelli et al[47] 2019	2	Vectra® H1	SP	DA	11	23 liner distances	The coefficient of variations for all distances ranged from 0.34% to 1.53% for repeatability, while ranged from 0.23% to 2.90% for reproducibility.
Staller et al[48] 2022	30	Bellus Face Camera Pro; 3dMD Trio	SP	DA	17	12 liner distances; 4 angles	All 3 methods showed excellent intraexaminer repeatability, except interpupillary distance measured by single-camera photogrammetry. Both single-camera photogrammetry and multicamera photogrammetry techniques were found to be reliable and valid options for 3D facial imaging.
Wang et al[49] 2022	20	iPad Pro 2020; ARC-7; EinScan Pro 2X Plus	SL	DA	12	14 liner distances	For the measurement of interlandmark distances, no significant differences were found. The 3 facial scanning systems provided a reliable 3D facial reconstruction.
Weinberg et al[50] 2006	20	Rainbow 250	SL	DA	17	19 liner distances	About one third of the linear distances differed between techniques, but in only 3/19 was the mean difference > 2 mm. The tested system is highly precise and shows high agreement with DA. Potential for clinical and research applications.
Wong et al[2] 2008	20	3dMDface	SP	DA	19	18 liner distances	The tested device is highly reliable($R = 0.91$), precise and accurate (error < 1 mm); its use in clinics is encouraged.
Ye et al[51] 2016	10	3dMD; Camega	SP; SL	DA	16	21 liner distances	No differences between instruments; absolute errors: SL 0.58 mm, SP 0.62 mm. Both optical systems are reliable and accurate with errors below the clinically acceptable threshold of 1 mm.
Zhao et al[3] 2017	10	FastScan; 3dMD	SL; SP	LS	9	surface-to-surface distance maps	RMSD between the facial maps: 0.5–0.7 mm; the 2 tested systems are both accurate and applicable for clinical purposes.
Zogheib et al[52] 2018	30	ProMax® 3D	LS	2D	15	5 liner distances;9 angles	Proportions linking the 3 facial regions in 3D were closer to the clinical standard (1.8% error rate).

*2D = two-dimensional, 3D = 3-dimensional, CR = cephalometric radiograph, CT = computed tomography, DA = direct anthropometry, LS = laser scanner, RGB-D = red, green, blue-depth, RMS = root mean square, RMSD = root mean squared distance, rTEM = relative technical error of measurement, SD = standard deviation, SL = structured light, SP = stereophotogrammetry, TEM = technical error of measurement.

al reported that the accuracy of measurement on volunteers was poor while the data collected from the mannequin was more accurate.[33] Through comparing the laser-based scanning with direct anthropometry, Kovacs et al found that the accuracy of laser scanners was low because the position of the scanned subject changed during the scanning process.[41]

In summary, laser-based scanning technique can be reliable to static objects; however, it can hardly meet the standards for 3D acquisition of facial soft-tissue measurement in living humans. In addition, laser scanners are cost-prohibitive, large, and stationary, which restrict their use in the clinical practice of stomatology.

3.3.2. Structured-light scanning. Based on the principle of optical triangulation, structured-light scanning technique can capture 3D information and generate 3D facial models by projecting structured grating fringes onto a subject's face, fringes are then transformed into measurement fringes when they pass through the measured subject.[54] A charged coupled device senses fringes produced by the face's morphology allowing the distance of each point in the pattern to be calculated and a 3D morphological information of the subject is created.[55]

Structured-light scanning technology was evaluated in 9 studies as the test method; direct anthropometry, laser-based scanning and stereophotogrammetry were used as reference method. Another 2 structured-light scanners were used as the gold standard in the studies.[27,43] Different from devices of other principles, structured-light scanning captures subjects more rapidly and inhibits any possible motion artifacts. It also has the advantages of high measurement accuracy, convenient operation and high security. FaceSCAN structured-light scanner of German 3D System company is 1 of the most widely used devices in clinical practice, which has a theoretical scanning accuracy of 0.1mm. A study conducted by Ye et al evaluated the accuracy and reliability of structured-light scanning technique compared with direct anthropometry, concluding that the measurement error of structured-light scanner is less than 1 mm, which can meet the clinical application.[51] The result of research conducted by Gomes et al demonstrated that the structured-light scanner showed excellent reliability in all/ measures, and the measurements accuracy was about 1 mm when the points were marked.[35]

In summary, instruments of structured-light scanning technique were considered acceptable for facial soft-tissue measurement in clinical practice of stomatology, even if their accuracy and precision were often worse than other devices. On account of its advantages of being cheaper and more portable, structured-light scanners are widely used in clinical practice.

3.3.3. Stereophotogrammetry. Based on the principle of binocular vision, stereophotogrammetry captures 3D facial surface data from at least 2 different positions using several cameras configured as a stereo pair.[56] The collected data were then processed and analyzed in the software to reconstruct a 3D images. This technique can combine images from multiple angles to form the 3D shape and size of face precisely, including the soft-tissue morphology and the facial surface color and texture.[57]

Sixteen studies tested stereophotogrammetry technology, the reference method including direct anthropometry, laser-based scanning, cephalometric radiograph and stereophotogrammetry. Stereophotogrammetry was also used as the reference method in 8 studies. Stereophotogrammetry was considered to be the gold-standard for facial soft-tissue measurement because of its rapid imaging speeds, low environmental requirements, high security and accuracy, convenient data storage and expanded surface coverage of up to 360°. The most widely used device is 3dMDFace System from 3dMD Company of United States, with a theoretical scanning accuracy of 0.2mm. Aynechi et al evaluated the accuracy of stereophotogrammetry, concluding that the soft-tissue images of the maxillofacial region obtained by 3dMDface system are accurate and reliable, especially when facial landmarks were labeled.[26] The portable stereophotogrammetry system was considered reliable and accurate with a high repeatability in the literature, although the presence of hair and involuntary movements of the mouth and eyes during the process can lead to larger discrepancies.[28,34]

In summary, stereophotogrammetry shows excellent precision for facial soft-tissue measurement. However, despite their advantages, instruments based on stereophotogrammetry are not practical for use in most clinical environments as they require extensive set-up and calibration times and high price, especially with the configuration of additional modules.

3.3.4. RGB-D camera. Recently, consumer-grade 3D scanning alternatives termed RGB-D camera based on computer vision technology have been developed. With the help of time of flight or structured-light technology, the so-called RGB-D camera is a sensor that can combine the RGB color of the object with the depth information of each pixel. Different from depth cameras that only express depth images, these devices output not only depth but also RGB images.[43]

RGB-D camera was tested in 6 recently published studies, stereophotogrammetry is the most commonly used reference, while direct anthropometry and structured-light scanning technology were also used in 2 studies. Due to the time of its application, RGB-D camera was not used as the reference method in published studies. Consumer RGB-D cameras with low cost, high measurement accuracy and fast measurement speed are widely used in standard clinical settings where traditional scanners are challenging to incorporate.[45] These portable devices can output color and depth information simultaneously, which avoids errors and loss of depth information frame caused during 3D reconstruction. Kinect camera is the first consumer RGB-D camera around the world. Maués et al evaluated the accuracy of Microsoft Kinect camera with DI3D system which is considered as a good scanner for the acquisition of facial soft-tissue morphology.[1] The result showed the difference between the 2 methods was 0.3 ± 2.03 mm, indicating the good precision and reasonable accuracy of Kinect camera for facial analysis. By comparing trueness and precision of the RGB-D camera with manual measurement, Raffone et al concluded that accuracy of RGB-D camera can be suitable for clinical use.[45]

In summary, when conventional 3D scanners are implausible in the clinical settings due to the limitation of resource and cost, RGB-D camera is considered to be an alternative to obtain facial soft-tissue morphology with good precision and reasonable accuracy.

4. Discussion

This systematic review was performed to summarize the use of 3D optical devices for facial soft-tissue measurement in clinical practice of stomatology with regard to the accuracy, precision and reproducibility. To improve reliability, only studies evaluating 3D optical devices in living subjects were included. Starting with more than 1300 automatically selected studies, the inclusion criteria and the analysis of the papers led to the selection of 38 articles for inclusion in this review, and most of the included studies had a low risk of bias. To our knowledge, this is 1 of the first reviews that focus on 3D optical devices for facial soft-tissue measurement in living subjects.

Twenty-two of the 38 studies used direct anthropometry as the reference method, thus liner distance is the most common measurement in this review. However, regarding to the assessment of RGB-D camera which is more portable, the stereophotogrammetry was used for reference, and surface-to-surface distance maps were evaluated. The participants included ranged from 2 subjects to 150 subjects. In most cases, there were more than 10 subjects, which validated the outcomes of the studies. However, the applicability of the current results to uncooperative people is still to be verified, for the reasons that no children or people with special needs were examined. The results of most studies indicated that the 3D optical devices provided clinically acceptable errors. Most of the artifacts come from involuntary movements of eyes and mouth, and these can be solved by high scanning speed of the instrument. Besides, although marking landmarks is time-consuming as well as laborious, prior facial landmarking is recommended before facial scanning.

3D optical devices are still in their infancy, a survey conducted by Fattah et al revealed that when assessing peripheral facial paralysis, only a small proportion of clinicians (18%) used 3D imaging, which indicates the limited clinical application of these devices.[58] It remains challenging for practitioners to confidently incorporate the technology into their clinical settings. Accordingly, in this study, we summarized the current evidence of 3D optical devices used in the clinical practice of stomatology, including oral and maxillofacial surgery, orthodontics and prosthodontics, so as to provide reference for their application in clinical settings.

Oral and maxillofacial surgery refers to address various oral and maxillofacial deformities and achieves functional reconstruction of defective tissues. The most widely used method for practitioners to predict postoperative outcomes and formulate surgical planning is combining the data of CBCT and digital photos in the software to obtain facial morphology.[59] Unfortunately, this method demonstrates poor accuracy in facial soft-tissue measurement due to the deviation caused by the complexity of facial morphology. With the help of 3D optical devices, the facial soft-tissue can be measured more accurately to achieve the best functional and aesthetic results and improve doctor-patient communication.[60,61] After evaluating the changes of facial soft-tissue before and 6 months after the surgery in 13 patients through CT and stereophotogrammetry, Ullah et al found that it is clinically acceptable to predict facial soft-tissue changes through 3D optical measurement.[62] Using 3D optical devices to assist the formulation of surgical plan and the evaluation of curative effect cleft lip and palate is another application in stomatology. By comparing 3D facial morphology between children with cleft lip and palate and healthy children using laser-based scanning, Djordjevic et al evaluated the effect of cleft lip and palate repair in an objective way.[63] Obstructive sleep apnea hypopnea syndrome (OSAHS) is a sleep breathing disorder characterized by sleep snoring and excessive daytime sleepiness, which often leads to disease in heart, lungs or other vital organs. MRI and cephalometry have been demonstrated to accurately measure the cranial and maxillofacial anatomical structures, which is related to the incidence of OSAHS. However, they are not suitable in most clinical settings due to the high cost of MRI and the radiation exposure of cephalometry. 3D optical devices with rapid imaging speeds and high accuracy can calculate the geodesic distance of facial soft-tissue to enhance the efficiency and reduce the cost of OSAHS prediction. These devices also overcome the limitation of conventional cameras, which cannot obtain nonlinear anatomical structures. Lin et al have established a predictive model for the occurrence and severity of OSAHS based on the measurement of facial morphology, whose accuracy is consistent with that of CT, higher than that of the prediction model established by 2D photography.[64]

Orthodontists rely heavily on facial soft-tissue assessment to determine facial aesthetics and treatment stability.[65] 3D optical devices can assist orthodontists in terms of diagnosis, treatment design and curative effect prediction in clinical practice. Due to the differences of facial contours among genders, regions and races, orthodontists should understand normal facial morphology of patients when formulating treatment plans, so as to achieve satisfactory effects. 3D optical devices can create the average facial features of normal people through data integration and analysis, so as to compare the facial morphology of different genders and regions.[66] In addition, these devices can also be integrated with dental-maxillofacial hard tissue obtained by CBCT or intraoral scanner, giving stronger technical supports for orthodontic treatment.

The measurement of facial soft-tissue morphology is also helpful for smile design and restoration in the aesthetic zone.[67] The traditional method of integrating digital photos and intraoral scanning using Photoshop or Keynote often results in deviation caused by the convexity of teeth and the difference of shooting angle in the process of aesthetic design of anterior teeth. With the application of 3D optical devices, the facial soft-tissue images obtained by these devices can match the digital dentition using CAD software to reconstruct a 3D virtual patient. With the help of digital technology, the aesthetic coordination effect of hard and soft tissues can be visually evaluated, which facilitates the communication among clinicians, patients and technicians, and achieves prosthodontic treatment with the goal of aesthetics.[68] Furthermore, the application of 3D optical devices in the aesthetic restoration of anterior teeth can shorten the initial wearing time of the restoration and improve the patient satisfaction with the prosthodontic effect.

5. Conclusion

In conclusion, the quantitative assessment of facial soft-tissue morphology is critical in the field of stomatology including diagnosis, treatment planning and evaluation of prognosis. Due to the high accuracy and good repeatability, 3D optical devices which emerged in the l990s have been demonstrated as a reliable method for the measurement of facial anatomy. Traditional static scanners have demonstrated excellent reliability in stomatology. RGB-D cameras with less requirements of resource, space and time are potential alternatives when clinical settings are limited. To maximize the advantages and minimize the limitations, clinical needs and availability of resources should be considered when selecting the most appropriate device. Suitable scanning device settings, prior facial landmarking, measurement accuracy control of involuntary facial movements and correct scanning protocols are also suggested in order to improve accuracy. The combination of dental-maxillofacial hard-tissue obtained by CBCT and facial soft-tissue captured by 3D optical devices is bound to be applied more extensively in the future with the continuous advancements in technology.

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