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SYSTEMATIC REVIEW

Accuracy of photogrammetric technologies for the scanning of dental models: A systematic review

Precisión de las tecnologías fotogramétricas para el escaneo de modelos dentales: Una revisión sistemática

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ABSTRACT

Background: Traditional dental scanners require a heavy investment, representing a high barrier of entry into digital dentistry. Photogrammetric-based scanners may represent an affordable cost-effective alternative to traditional dental scanners used for the digitalization of plaster models. Photogrammetry is the science of extracting 3D information from photographs. The process involves taking overlapping photographs of an object or space and converting them into 2D or 3D digital models.
Objective: This review aimed to identify and appraise the reported accuracy of photogrammetric-generated digital dental models.
Materials and methods: A search strategy was applied in 3 databases (Medline, Web of Science and Scopus), from Feb 1 2021 to Dec 1 2021, the search was limited to articles in English published in the last 5 years about studies evaluating the dimensional accuracy of 3-dimensional digital models acquired by the scanning of plaster models with photogrammetric technologies.
Results: Two independent reviewers screened 75 records on basis of titles and abstracts for assessment against the inclusion criteria for the review, 4 articles were deemed eligible, the risk of bias for the selected articles was measured, data extraction was performed by only one author.
Conclusion: With today's technology, based on the four studies evaluated, we conclude that photogrammetric-generated digital models while lacking accuracy for incorporation into the treatment flow, in the future it could be used for diagnostic, planning, and achieving.

KEYWORDS
3D Models; Budget; Structure-from-motion; Trueness; Precision.

RESUMEN

Antecedentes: Los escáneres dentales tradicionales requieren una gran inversión, lo que representa una gran barrera de entrada a la odontología digital. Los escáneres basados en fotogrametría pueden representar una alternativa asequible y rentable a los escáneres dentales tradicionales utilizados para la digitalización de modelos de yeso. La fotogrametría es la ciencia de extraer información 3D de fotografías. El proceso implica tomar fotografías superpuestas de un objeto o espacio y convertirlas en modelos digitales 2D o 3D.
Objetivo: esta revisión tuvo como objetivo identificar y evaluar la precisión informada de los modelos dentales digitales generados fotogramétricamente.
Materiales y métodos: Se aplicó una estrategia de búsqueda en 3 bases de datos (Medline, Web of Science y Scopus), del 1 de febrero de 2021 al 1 de diciembre de 2021, la búsqueda se limitó a artículos en inglés publicados en los últimos 5 años sobre estudios que evalúan la dimensión precisión de modelos digitales tridimensionales adquirida por el escaneo de modelos de yeso con tecnologías fotogramétricas.
Resultados: dos revisores independientes examinaron 75 registros sobre la base de títulos y resúmenes para evaluarlos según los criterios de inclusión para la revisión, 4 artículos se consideraron elegibles, se midió el riesgo de sesgo de los artículos seleccionados, la extracción de datos fue realizada por un solo autor.
Conclusión: con la tecnología actual, con base en los cuatro estudios evaluados, concluimos que los modelos digitales generados por fotogrametría si bien carecen de precisión para incorporarlos al flujo de tratamiento, en el futuro podrían usarse para el diagnóstico, la planificación y el logro.

PALABRAS CLAVE
Modelos 3D; presupuesto; estructura a partir del movimiento; veracidad; precisión.

CLINICAL RELEVANCE

Current advancements in optics and software have made photogrammetry an unexpensive 3D scanning solution. This study aims to show the capabilities of photogrammetry to digitalize dental models. The future deployment of this technology could make digital dentistry accessible to impoverished communities in the developing world.

INTRODUCTION

Dental casting is a routine procedure in the orthodontic consult to record the oral tissues. The generated casts are used for diagnostic purposes, treatment planning, fabrication of orthodontic appliances and indirect bonding trays, communication with the patient and evaluation of treatment results.[1] Being part of the dental records, they must be kept for an average of 5 years depending on the state,[2] this represents a significant storage problem, during which time they are prone to get lost or fractured. Digital dental models eliminate the problems associated with the physical storage of plaster models.[1,3]

Unfortunately, most dental scanners can be quite expensive, making for a high barrier of entry into the digital workflow. Photogrammetry is a potential low-cost alternative for acquiring digital models compared to dental scanners.

Photogrammetry is the art and science of extracting 3D information from photographs. The process involves taking overlapping photographs of an object, structure, or space, and converting them into 2D or 3D digital models.[4,5] Photogrammetry is said to be as old as photography. In 1759, Lambert, a German mathematician published a treatise on how to reconstruct three-dimensional objects from perspective drawings. In 1839, Arago, a French physicist wrote that photography could be used to measure the tallest and most inaccessible buildings and replace surveyors. The first photogrammetrist was Laussedat, a French military officer in 1849, but it was Meydenbauer, a German architect who coined the term "photogrammetry".[6] Photogrammetry is now a well-established three-dimensional measurement technique, routinely used in a wide range of disciplines, from its use in surveying to its use in healthcare. In orthodontics, photogrammetry is used to digitize the patient's face, allowing us to perform digital soft tissue diagnostics.[6-13]

For a dental model, be it physical or digital, to be of any use, it needs to accurately represent the oral tissues of the patient. Therefore, for the photogrammetric scanners to be recommended for orthodontic use, they should possess an accuracy that is, at least, close to conventional alginate impressions. For conventional impressions, the limit for changes in linear dimensions is 0.5% according to the American National Standards Institute/ American Dental Association (ANSI/ADA) specification no.19 [14,15] and ISO 4823 (International Organization for Standardization).[16] The physiological constant movement of the tooth in the mesio-distal direction has been reported to be of approximately 30 to 100µm,[17] deviations below this range are clinically acceptable.[18]

The ISO 5725 of measurement methods and results, describes accuracy with two terms, precision, and trueness. Precision describes the closeness of the dimensions of repeated measurements to each other. High precision is related to a more repeatable and consistent measurement. Trueness describes the extent to which the dimensions obtained deviate from the actual dimensions of the measured object. For an instrument to be considered accurate, it must have high precision and trueness.[19]

There are multiple articles reporting the use of photogrammetric scanners to accurately digitalize patients faces for digital anthropometric measurements, and orthodontics' facial diagnosis [20–25] or even for the fabrication of facial prostheses.[10]

A preliminary search of PROSPERO [26] was conducted for current or underway systematic reviews on photogrammetry, 23 records were identified, focusing on the use of photogrammetry for Soft tissue or skeletal morphology. As of December 2021, no current or underway systematic reviews regarding the accuracy of photogrammetric technologies for the scanning of dental models. Therefore, the objective of this systematic review was to evaluate the reported accuracy (trueness and precision) of photogrammetric scanners, as they have the potential to be a practical and more affordable alternative for digitizing plaster models, and thus lowering the barrier to entry for dentists to a digital workflow.

MATERIALS AND METHODS

The proposed systematic review was conducted in accordance with the Joanna Briggs Institute methodology for systematic reviews of diagnostic test accuracy.[27] And in adherence to the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses. (PRISMA).[28]

The question of this systematic review is, how is the accuracy of the photogram-metric scanners relative to conventional impressions or even digital dental scanners?

Registration:

A protocol for this review was registered in the Research Committee of the Faculty of Stomatology of the Benemerita Universidad Autónoma de Puebla, with registration number 2021154.

Search Strategy

An electronic search of the literature was conducted through PubMed (MEDLINE), Web of Science and Scopus from Feb 1, 2021 to May 10, 2021. The Boolean operators of the PubMed database were utilized to combine the following terms: ('Dental models' OR 'Dental casts' OR 'plaster models' OR 'plaster casts' OR 'orthodontic models' OR 'orthodontic casts' OR 'stone casts') AND ('photogrammetry') NOT ('cleft lip' or 'posture') The search strategy, including all identified keywords and index terms, was adapted for each included database and/or information source (See Appendix A). The reference lists of all included sources of evidence were screened for additional studies.

The search aimed to collect all the articles that investigated the accuracy of photogrammetric scanners. Due to the rapid change in technology we decided to limit our search to the last 5 years, we seek to evaluate the state of photogrammetric scanners with up-to-date technology.

Eligibility Criteria

To be considered for inclusion, the articles had to been published in English in the last 5 years in a peer-reviewed journal, evaluating the dimensional accuracy of 3-dimensional digital models acquired by the scanning of plaster models with photogrammetric technologies. The articles were excluded if the context of their research was about implant component scanning, involved the scanning of facial tissues or focused on posture tracking.

Study Selection

Following the search, all identified articles were collated and uploaded into a reference software (Mendeley, Version 1.19.8, Mendeley Ltd). The software was used to eliminate the duplicated articles from the different searches (J.E.G.V.). Following a pilot test, titles and abstracts were screened by two independent reviewers for assessment against the inclusion criteria for the review using the Abstrackr Web tool (J.E.G.V., C.SV.) .[29]

Potentially relevant studies were retrieved in full. The full texts of selected citations were assessed in detail against the inclusion criteria by two independent reviewers (J.E.G.V., C.SV.). If there were any discrepancies, a third reviewer was consulted (R.C.G.).

Selected studies were critically appraised by two independent reviewers using the Quality Assessment of

Table 1. Quality Assessment of Diagnostic Accuracy Studies (QUADAS) guidelines and scoring system.

(QUADAS) guidelines and scoring system	Yes	No Unclear
Was the spectrum of arches/teeth representative of what will be diagnosed in practice?		
Were the selection criteria clearly described?		
Is the reference method likely to correctly classify the target condition?		
Is the time period between reference method and test method short enough to be reasonably sure that the target condition did not change between the two tests?		
Did the whole sample, or a random selection of the sample, receive verification using a reference standard of diagnosis?		
Did the arches/teeth receive the same reference method regardless of the test method results?		
Was the reference method independent of the test method (i.e. the test method did not form part of the reference standard)?		
Was the execution of the test method described in sufficient detail to permit replication of the test?		
Was the execution of the reference method described in sufficient detail to permit its replication?		
Were the test method results interpreted without knowledge of the result of the reference method?		
Were the reference method results interpreted without knowledge of the results of the test method?		
Were the same clinical data available when test results were interpreted as would be available when the test is used in practice?		
Were uninterpretable/intermediate test results reported?		
Were withdrawals from the study explained?		

Diagnostic Accuracy Studies (QUADAS) tool to measure the risk of bias of the included studies.[30] This was achieved by asking 14 questions (Table 1), for every study. For each question, a score of 1 was given if the answer is "yes". If the answer was "no" or "unclear", a score of 0 was given. Therefore, the highest possible score, indicating a lower risk of bias, is 14. Results reported visually using the robvis tool.[31]

Any disagreements that arose was resolved through discussion. All studies, regardless of their methodological quality, underwent data extraction.

Assessment of methodological quality

Selected studies were critically appraised by two independent reviewers using the Quality Assessment of Diagnostic Accuracy Studies (QUADAS) tool to measure the risk of bias of the included studies.[30] This was achieved by asking 14 questions (Table 1), for every study. For each question, a score of 1 was given if the answer is "yes". If the answer was "no" or "unclear", a score of 0 was given. Therefore, the highest possible score, indicating a lower risk of bias, is 14. Results reported visually using the robvis tool.[31]

Any disagreements that arose was resolved through discussion. All studies, regardless of their methodological quality, underwent data extraction.

Outcome variables

For this systematic review, only the data on accuracy was extracted. For each study, the following information was collected and summarized in Tables 3-4: author names, year of publication, control/reference scanner, sample description & size, evaluation method and accuracy outcome. A meta-analysis was not feasible because of the data's heterogeneity. The accuracy of the different photogrammetric scanners was evaluated by:

1. Dimensional measurements: Measuring the distance between predetermined pair of points on the digital models generated with the photogrammetric scanners and comparing it to the distance between similar pairs on a physical model or a reference digital model.
2. Superimposition accuracy: Using the principles of best-fit-alignment, two or more digital models are superimposed. This method allows us to measure 2 variables:
   •Trueness: Comparing the photogrammetric-generated digital model with the reference digital model.
   •Precision: Comparing the similarity of multiple digitalization of the same physical model by the same photogrammetric scanner. The precision reflects the repeatability of using a given photogrammetric scanner.

Table 2. Details of all the investigated photogrammetric scanners by the included studies.

Study (year)	Technical details	Camera distance to object	Aperture/ ISO	Shutter Speed	Depth of field	Vertical tilting angle	Camera/ Object angle of rotation. Manual or automatic	Number of photos per rotation/ Total	Surface treatment
Santosi (2018)[17]	Canon 1200d DSLR with a 18-55 mm lens set at 55mm Agisoft Photoscan	50cm (± 5cm)	F18/Not disclosed	Not disclosed	5 cm	2 vertical planes, distance or angulation not disclosed.	90 ° Manually rotation of the object	8 / 32	None Video projector set up at a distance of 75cm and at an angle of 50° for random and wavelet pattern
Silvester & Hillson (2020)[19]	Canon EOS6D (20.2mega	Not disclosed.	F11/100	1/40s	Not disclosed	Wooden adjustable arm,	22.5° Automatic rotation of the object	5/80	None

	pixels) with 100 mm macro lens Agisoft Metashape					angles of 2°, 12°, 21°, 31° and 45°			
V.T. Stuani (2019)[20]	Canon EOS Rebel T3i with Macro lens EF 100 mm 3DF Zephyr Free® software	45 cm	F32/100	Not disclosed	Not disclose d	0°, 45° and 90° from the PM occlusal plane.	15° not disclosed if the object or the camara did the rotations.	2/50	None
Fu (2017)[21]	Canon EOS 600D with a 90 mm prime lens Meshlab	45 cm	F22/ Not disclosed	Not disclosed	Not disclose d	0° and 40°	20° Manually rotation of the camera	4/72	None

Table 3. Dimensional measurements studies.

Study (year)	Study quality score (0-14)	Control / Reference scanner	Sample description (material)	Sample size	Evaluation method	Accuracy
Clinical studies						
V.T. Stuani (2019) [20]	12	Physical plaster model measured with a digital caliper equipped with a resolution of 0.01 mm	Plaster model of the upper jaw	1 physical model	Dimensional measurements between predefined pair of points.	Trueness, height and thickness -0.4 to 0.6 mm Precision SD of ± 0.171 and a repeatability coefficient of 0.474
Fu (2017)[21]	12	Physical plaster model measured with a digital caliper equipped with a resolution of 0.01 mm	Sets of plaster models of the upper and lower jaw.	60 models (30 sets)	Dimensional measurements between predefined pair of points.	Trueness, Mean differences for: Mesio-distal width: 0.011 to 0.016 mm Arch width: 0.108 to 0.154 mm.

The lower the discrepancy, the higher the trueness and precision.

RESULTS

Study selection

A total of 106 articles were retrieved from the initial electronic search. All identified articles were collated and uploaded into a reference software to remove duplicates (Mendeley, Version 1.19.8, Mendeley Ltd), which left us with 75 articles. An additional 69 articles were excluded after screening for title and abstract relevance, leaving us with a total of 6 articles for full-text reading. After the detailed assessment against the inclusion criteria, 4 articles were suitable for inclusion in this review.[32-35] The study by Alyaman et al.[36] was excluded because it was limited to a naked-eye, qualitative examination of the digital models, and the Arapović et al. [37] study was excluded as it involves two-dimensional photogrammetry (Figure 1).

Characteristics of included studies

The articles included were experimental and prospective studies. The evaluated photogrammetric scanners were summarized in Table 2. According to QUADAS guidelines,[30] the studies' quality scores ranged from 11 to 12 (out of 14). (Figure 2.) The digitalized objects were plaster dental models. Some of the studies digitalized plaster models with prepared teeth, while others were on unprepared teeth. All 4 studies [32–35] utilized monoscopic photogrammetric scanners, (scanners with a single Canon DSLR camera) and rotated either the camera or the object. In addition, all 4 tried to systemize the image acquisition, but only Silvester and HiIllson's study [33] used an automatic turntable to rotate the object. Out of the 4 studies, only Santosi et al.[32] study used a surface treatment to improve the digitalization of the model, they projected a light pattern over the plaster model. The number of photos taken per digitalization in all 4 studies ranged from 32 – 80 photos.

The control groups were digital models obtained with structured-light professional scanners or the measurement of the physical plaster models with digital calipers.

Main findings

Dimensional measurements studies

Two studies evaluated the accuracy of dimensional measurements on the digital models generated with photogrammetric scanners compared against measurements made on the physical model with a digital caliper (Table 3).

Fu et al.,[35] reported that the average differences between the measurements of the digital models and the physical models were 0.011–0.402 mm. The mean differences were not significant except for the lower arch perimeter ($P>0.05$), all the differences were deemed as clinically acceptable (<0.5 mm) Similarly, Stuani et al.[34] found a limit of agreement between −0.433 and 0.611 mm among the measurements on the digital and physical models.

Superimposition accuracy studies

Three articles evaluated the superimposition accuracy of the digital models generated with the photogrammetric scanners. (Table 4).

Santosi et al.,[32] photogrammetric scanner utilized a projector to light a pattern over the plaster model to generate a more accurate digital model, after CAD inspection they reported a prealigment best fit Standard deviation of ±0.096 mm (Without pattern), ±0.081 mm (Random pattern) and ±0.074 mm (Wavelet pattern).

Silver and Hillson [33] reported a trueness of 57 to 159 µm, finding the use of photogrammetric scanners for model acquisition to be highly replicable (59 to 90 µm) and the digital models generated could be used to obtain crude quantitative size and shape data, nonetheless, finer scale surface details are not accurately reproduced with the photogrammetric scanner they evaluated.

Stuani et al.,[34] used the superimposition to evaluate the precision on the 5 digital models obtained from a single plaster model with their photogrammetric system, finding a precision mean difference of −0.5 mm to 0.5 mm ± 0.171.

DISCUSSION

Conventional impressions are still the gold standard for comparison, they are used by several studies as control methods against intra and extra oral systems, including photogrammetric scanners.[38] During the conventional impression workflow, every material handled, and every step will contribute to the final discrepancy. This includes but is not limited to the impression material setting, impression removal and stone material setting[39,40].

Alginate impression is commonly used to obtain diagnostic models, it exhibits the least accuracy of the conventional impressions' materials, but its accurate enough (162 ± 71.3 µm) for the orthodontic diagnosis.[40] Previous studies by Asquith et al.[41] Okunami et al. [42] and Leifert el al. [43] postulated the limits of clinical acceptability; differences of less than 0.5 mm for single-tooth measurements and/or less than 5 per-cent of the distance of arch width, arch length and arch perimeter measurements are to be considerate

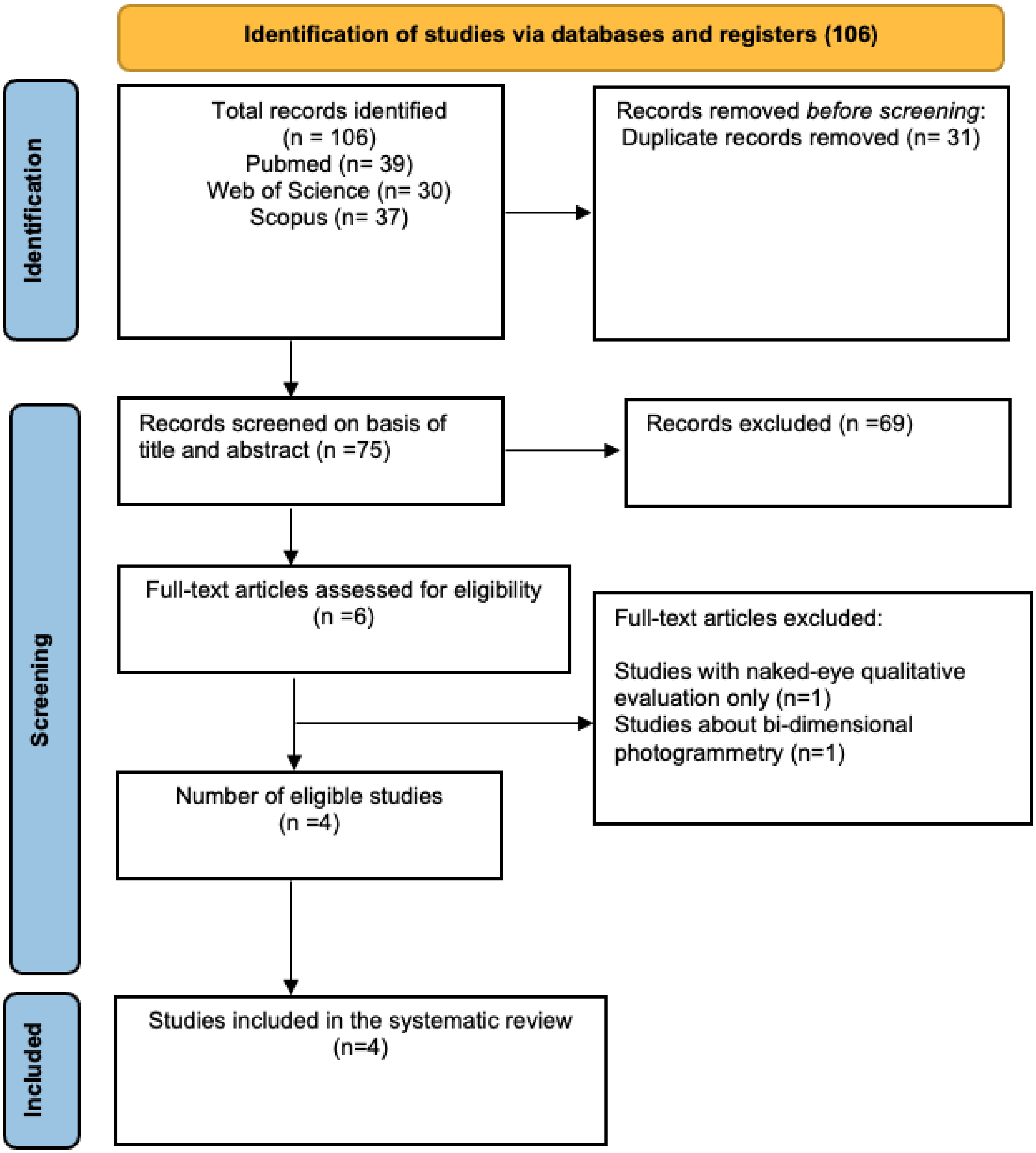

Figure 1. PRISMA flow diagram of record processing and elimination

Table 4. Superimposition accuracy studies.

Study (year)	**Study quality score (0-14)**	**Control / Reference scanner**	**Sample description (material)**	**Sample size**	**Evaluation method**	**Accuracy**
Clinical studies						
Santosi (2018)[17]	11	Plaster model digitalized with an Atos II Triple Scan from GOM	Plaster model of the upper jaw with abutments without pattern, random patter and wavelet pattern	1 model	Superimposition against 3D model obtained from reference scanner to measure trueness	CAD inspection prealignment best fit standard deviation [mm] Without pattern +0.096 Random pattern +0.081 Wavelet pattern +0.074
Silvester & Hillson (2020)[19]	12	Plaster model digitalized with an ATOS 80 Scanner from GOM	Plaster model of the lower jaws obtained using a two-phase, two-step, putty-wash technique,	17 models	Superimposition against 3D model obtained from reference scanner to measure trueness.	Trueness Mean differences 57 to 159 μm Precision Mean differences: 59 to 90 μm
V.T. Stuani (2019)[20]	12	The same plaster model digitalized 5 times with the photogrammetric system	Digitalized Plaster model of the upper jaw	5 digital models	Superimposition against 5 3D models obtained from the same plaster model.	Precision −0.5 mm to 0.5 mm

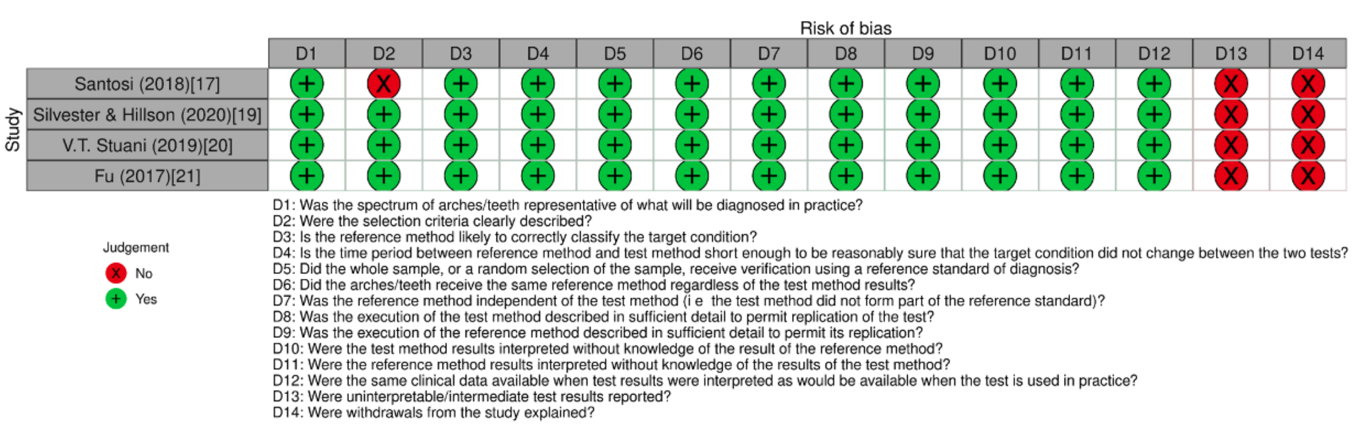

Figure 2. QUADAS quality assessment of studies of diagnostic accuracy

clinical acceptable.[41–43] Since the accuracy of the photogrammetric systems [32–35] were found to be within this range, it can be assumed that the photogrammetric-generated digital models can be safely used for diagnostic purposes. However, further research is needed to reach a definitive conclusion.

This systematic review shows that the limited studies included had considerable heterogeneity in terms of evaluation methods, scanners evaluated (Hardware and software), control groups and parameters used (Photos per rotation, angles of inclination, etc). This reflects on the outcomes of the studies.

On the heterogeneity of the scanners, it is important to note that photogrammetric scanners are all those devices or gadgets that allow us to systematize the taking of photographs for use in photogrammetry, its complexity and cost are variable. These can be complex systems of multiple synchronized cameras [20,23,25] or a single camera. [22] It is important to remember that the photogrammetry itself, i.e. the generation of the 3D model, is performed on computers by specialized software, the "scanner" only systematizes the first step in the process, the taking of photographs. [44]

For instance, Silvester and Hillson [33] reported a steep decrease in point cloud density in image sets of <70 images, reason for which they opted for a set of 80 images. The other 3 studies had sets of 32,[32] 50 [34] and 72 [35] images. We could also look at the photogrammetric software utilized by the distinct authors, Santosi et al. [32] in 2018 used Agisoft Photoscan, which in 2019 was renamed to Agisoft Metashape, adding the use of GPU and AI among other improvements. Agisoft Metashape was used by Silvester and Hillson [33] in 2020. Stuani et al. [34] used the limited free version of 3DF Zephyr, while Fu et al. [35] reports to have used the open-source software Meshlab, but this is not a photogrammetric software, it's a mesh manipulation software [45]. The use of a particular photogrammetric software over other, can have a meaningful impact on the reported accuracy, as shown by the multiple studies comparing the effect on accuracy when using different photogrammetric softwares to process the same data sets [46,47].

There are arguably better photogrammetric software solutions in the market than the ones used in the included articles, it could be hypothesized a possible improvement in accuracy in these studies if they were to use larger image sets and/or a more potent and robust photogrammetric software such as Capturing Reality.

The two biggest challenges for photogrammetry in general are shinny surfaces and featureless surfaces, both challenges can be overcome with surface treatment of the target object.[48] As mentioned previously, out of the 4 studies, only Santosi et al.[17,32], study used a surface treatment by projecting a light pattern over the plaster model. Neither of the 4 studies used chalk spray on the plaster models, powdering the target object has been demonstrated to aid in their digitalization.[49]

The authors literature search only came up with four studies, [32–35] this is both our biggest strength and our biggest weakness, it suggests a dire need for more research on the potential of photogrammetric technologies as a cost-effective way to digitalize plaster models. This is especially true when we consider the ever-improving hardware and software required for photogrammetry. Neither of the 4 studies included used the RealityCapture photogrammetric software, arguably one the fastest and most robust software in the market, [47] although it's quite expensive, it has free licenses for universities, with that in mind, we would like to see further research into this subject.

As previously mentioned, powdering the models could greatly enhance their digitalization [49] for this reason we suggest to future researchers or clinical users the use of chalk spray on the plaster models to increase the number of features the photogrammetric software picks up, which would in turn generate a better digital model.

As Gruen [50] mentions, photogrammetry at times appears to be a ´secret technology´ that the public hasn´t familiarize itself with, despite of it permeating our daily life: Video games, movies, Maps, bio-medical systems, automatic goal detection systems in sports, etc, This lack of general familiarity with the photogrammetric technology results troublesome, for it is here to stay. In the words of John G. Fryer [5]:

“Despite all the exciting possibilities for 3D imaging techniques, users of this technology must keep in mind [that] light will continue to travel in straight lines and an understanding of geometry will be just as valid tomorrow as it is today”.

Finally, this systematic search limited itself to the accuracy of the photogrammetric scanners, it didn't consider the time it takes for a digital dental model to be generated. While unexpensive, photogrammetry does take a lot of computational power, and can get to be quite time consuming, depending greatly on the photogrammetric software chosen, [46,47] this too is something we would like to see evaluated in future research.

CONCLUSIONS

With today's technology, based on the four studies evaluated, we conclude that photogrammetric-generated digital models while lacking accuracy for incorporation into the treatment flow, in the future it could be used for diagnostic, planning and achieving, dispensing the need for large spaces to store physical models and facilitate the clinical organization.

DECLARATION OF CONFLICT OF INTEREST

All authors of this manuscript declare that they do not have competing financial interests or personal relationships that could influence the work reported in this paper.

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