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Accuracy of full-arch digital implant impressions taken using intraoral scanners and related variables: A systematic review

KEY WORDS

accuracy, dental impression technique, digital impressions, edentulous, intraoral scanner

ABSTRACT

Purpose: To evaluate the accuracy of full-arch digital implant impressions taken using intraoral scanners and analyse the related variables.

Materials and methods: An electronic search of studies on the accuracy of digital implant impressions in fully edentulous arches from 1 January 2012 to 29 February 2020 was conducted in PubMed, EMBASE and the Cochrane Library. Only peer-reviewed experimental or clinical studies written in English were included. Studies assessing the accuracy of restorations, case reports, clinical reports, technical reports and reviews were excluded. The literature screening, article reading and assessment of risk of bias were carried out by two reviewers. The data on the study characteristics, accuracy outcomes and investigated variables were extracted.

Results: After removal of duplicates, a total of 166 studies were identified, of which 42 were initially selected for full-text reading and 30 were included in the final analysis (29 in vitro studies and one in vivo study). The trueness of digital implant impressions ranged from 7.6 to 731.7 µm, and the precision ranged from 15.2 to 204.2 µm. Angular deviations were between 0.13 and 10.01 degrees. Considering 100 µm and 0.4 degrees as clinically acceptable levels of deviation, 18 studies reported linear/distance/3D deviations larger than 100 µm and only two studies reported angular deviations below 0.4 degrees. The effect of interimplant distance/length of the arch scanned/scanning sequence/scanning range/implant position (nine studies), implant angulation (ten studies), implant depth (five studies), implant connection (two studies), operator experience (six studies), scan body type (three studies), intraoral scanner type (six studies), scanning strategy (two studies) and modification technique (three studies) was investigated.

Conclusions: Based on the results of the included studies, full-arch digital implant impressions taken using intraoral scanners are not sufficiently accurate for clinical application. Accuracy varies greatly with interimplant distance, scan body type, intraoral scanner type and operator experience, whereas implant angulation, implant connections and implant depth have no effect. The effects of scanning strategy and modification technique need further investigation.

Conflict-of-interest statement: *The authors declare there are no conflicts of interest related to this study.*

Introduction

Digital implant impressions (DIIs) taken using intraoral scanners (IOSs) have developed rapidly over the past decade. IOSs employ different principles to directly capture images of dentition and soft tissues intraorally and generate 3D virtual models[1]. For DIIs, the scan body is connected to implants and the latter are scanned to indicate their position. The virtual models are then converted to stereolithography (STL) files and imported into software so restorations can be designed.

Unlike conventional implant impressions (CIIs), DIIs avoid the risk of distortion and the need for casting materials[2], and thus reduce waste and do not require transportation of physical casts[3,4]. DIIs are considered more comfortable than CIIs[5] since the gag reflex and the unpleasant odour of impression materials are avoided.

Despite their advantages, the accuracy of DIIs remains a major concern. Accuracy refers to trueness and precision (ISO5725-1); trueness describes the closeness of measurements to the actual values, and precision describes the closeness of multiple repeated measurements[6]. Accurate impressions are fundamental to the passive fit of restorations and the success of implant treatment[7]. Biological and mechanical complications, such as bone resorption, screw loosening, component fracture and even loss of implants or prostheses, may occur due to misfit between implants and superstructures[8,9].

Although previous studies have reported that digital impressions of single implants taken using an IOS showed satisfactory accuracy and efficiency in clinical practice[10-12], digital impressions of multiple implants, especially in completely edentulous arches, demand higher accuracy and present greater difficulties. Since an IOS can only capture images or videos of a limited area and generates the final models by stitching the images together[13,14], the lack of landmarks in completely edentulous arches[15-17], long span of mobile mucosa[17] and multiple identical scan bodies used[15,18,19] may cause the images to be stitched incorrectly and generate higher deviations[13,17,18,20]. As IOS equipment and modification techniques continue to evolve, an increasing number of studies assessing the accuracy of DIIs in edentulous arches have emerged, but reached inconsistent conclusions. As such, the present authors conducted a systematic review to evaluate the accuracy of full-arch DIIs taken using IOSs and summarise the related variables.

Materials and methods

The present systematic review was conducted under the guidance of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist.

Focus question

The patient, intervention, control and outcome (PICO) question was "What are the accuracy outcomes of full-arch DIIs taken using IOSs and the related influencing variables?"

Search strategy

An electronic search of PubMed, EMBASE and the Cochrane Library was conducted to identify articles published from 1 January 2012 to 29 February 2020. An additional manual search of the International Journal of Oral & Maxillofacial Implants, Clinical Oral Implants Research, Clinical Implant Dentistry and Related Research, the Journal of Prosthodontics, the Journal of Prosthetic Dentistry, the International Journal of Prosthodontics, the International Journal of Oral Implantology, Implant Dentistry and the Journal of Computerized Dentistry was performed. The reference lists of the articles selected for full-text review were also searched manually. The following main search strategy was established for PubMed: (dental implant [MeSH terms] OR dental implant*) AND (digital OR optical OR intraoral OR intra-oral) AND (dental impression technique [MeSH terms] OR impression*) AND (accuracy), yielding 150 results. It was adjusted for Embase to (dental AND implant*) AND (digital OR optical OR intraoral) AND (impression*) AND (accuracy), and for the Cochrane Library to (dental implant) AND (digital OR optical OR intraoral) AND (impression) AND (accuracy), yielding 123 and 3 results, respectively.

Study selection

The titles and abstracts of all the records were initially screened to select articles for full-text review. The full texts of the selected articles were then read carefully and assessed for eligibility. The literature screening and reading were performed by two independent reviewers (YZ and JS). Any disagreement about the eligibility of articles was discussed and resolved with a third reviewer (SQ).

For inclusion, the studies needed to assess the accuracy of DIIs taken using IOSs at an implant/abutment level, have been performed in completely edentulous arches in vivo or in vitro, and be experimental or clinical studies included in peer-reviewed journals published in English.

Studies assessing accuracy by measuring marginal gaps or observing the space between restorations and implants and abutments were excluded since the errors generated in the restoration manufacturing process could not be measured separately. Case reports, clinical and technical reports, reviews and studies without a clearly stated methodology were also excluded.

Risk of bias assessment

Quality assessment of the included studies was performed using the modified methodological index for non-randomised studies (MINORS) (Table 1)[21-23]. This tool consisted of nine criteria for all the studies and two criteria added specifically for in vivo studies. Each subject was scored as 0, 1 or 2. In most cases, the scores of 0, 1 and 2 referred to "subjects not reported", "subjects reported but inadequate" and "subjects reported and adequate", respectively. The maximum possible score was 18 for in vitro studies and 22 for in vivo studies. Two reviewers (YZ and JS) scored 30 studies independently, and any disagreement was discussed and resolved with a third reviewer (SQ).

Data extraction

The following information was extracted from both in vivo and in vitro studies:

- study type (in vitro or in vivo);
- study model or clinical scenario (arches, number of implants, implant position, implant angulation, implant depth, connection type, impression level);
- scanning process (scan body type, IOS type, scanning strategy, operator experience);

Table 1 Risk of bias assessment using modified methodological index for nonrandomised studies (MINORS)

Criteria	Scoring
Clearly stated aim	0, not reported; 1, reported but inadequate; 2, reported and adequate
Contemporary groups	0, not reported; 1, reported but inadequate; 2, reported and adequate
Digital impression method	0, not reported; 1, reported but inadequate; 2, reported and adequate
Adequate control group	0, not reported; 1, reported but inadequate; 2, reported and adequate
Accuracy assessment method	0, not reported; 1, reported but non-quantitative; 2, reported and quantitative
Blinding of observer or statistician	0, not reported; 1, reported but inadequate; 2, reported and adequate
Adequate number of observations	0, 5–9; 1, 10–14; 2: 15+
Prospective calculation of study size (justification of specimen size for both experimental and control groups needed to determine statistical significance)	0, not reported; 1, reported but inadequate; 2, reported and adequate
Adequate statistical analysis	0, not reported; 1, reported but inadequate; 2, reported and adequate
Additional criteria for included in vivo studies	
Prospective collection of data	0, not reported; 1, reported but inadequate; 2, reported and adequate
Baseline equivalence of groups	0, not reported; 1, reported but inadequate; 2, reported and adequate

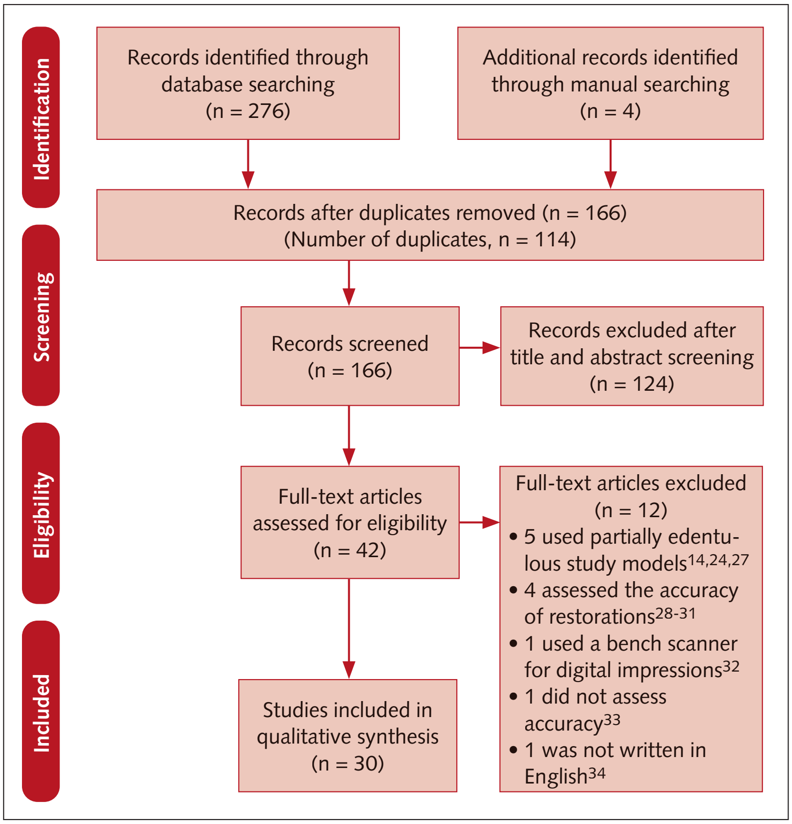

Fig 1 PRISMA flow diagram of search strategy and study selection.

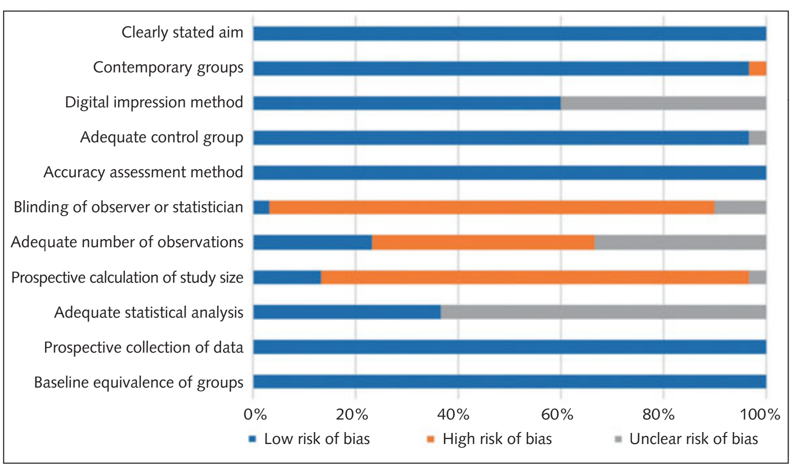

Fig 2 Risk of bias according to modified MINORS.

- study design (sample size, methods of accuracy measurements);
- accuracy outcomes of DIIs and CIIs;
- evaluated variables and their effects (interimplant distance, implant angulation, implant depth, implant connection, operator experience, scan body type, IOS type, scanning strategies, modification techniques).

Results

Included studies

The initial search resulted in 280 records, and 166 after removal of duplicates. After screening the titles and abstracts, 42 articles were selected for full-text reading. Twelve studies were excluded for reasons listed in the PRISMA flow diagram[14,24-34]. A total of 30 studies were included in the systematic review (Fig 1).

A risk of bias assessment was performed using the modified MINORS tool. A complete description of the assessment is displayed in Table 2. Except for one in vitro study and one in vivo study, most of the studies scored equal to or less than 14, indicating a high risk of bias; however, in all the studies, the aims were stated clearly and the accuracy measurement methods were described fully (Fig 2).

Study characteristics

The studies included in the present systematic review consisted of 29 in vitro studies and one in vivo study. A detailed description of the study characteristics is provided in Table 3.

Methods of accuracy measurement

Different methodologies were applied for accuracy measurement. Overall 3D deviations, linear/angular deviations and the distance/angular deviations between paired scan bodies were the three main types of accuracy outcomes.

The first approach superimposed the test STL files of the impression techniques onto the corresponding reference scans obtained using coordinate measurement machines (CMMs; 1 μm accuracy) or laboratory scanners (5 to 10 μm accuracy) according to a best-fit algorithm and provided 3D deviations. The 3D deviations described the mean difference between the point clouds of the test and reference scans, representing the overall deviations. In total, six studies assessed the 3D deviations of DIIs[1,18,35-38].

The second approach to obtaining linear and angular deviations involved defining the reference

Table 2 Risk of bias assessment for the included studies

Study	Criteria											Total score
	Clearly stated aim	Contemporary groups	Digital impression method	Adequate control group	Accuracy assessment method	Blinding of observer or statistician	Adequate number of observations	Prospective calculation of study size	Adequate statistical analysis	Prospective collection of data	Baseline equivalence of groups	
Andriessen et al[17]	2	0	2	1	2	0	2	0	2	2	2	15
Alikhasi et al[39]	2	2	1	2	2	0	2	1	1	NA	NA	13
Amin et al[35]	2	2	2	2	2	0	1	2	1	NA	NA	14
Arcuri et al[40]	2	2	1	2	2	1	2	0	2	NA	NA	14
Ciocca et al[41]	2	2	2	2	2	0	0	2	1	NA	NA	13
Di Fiore et al[42]	2	2	2	2	2	0	2	0	1	NA	NA	13
Giménez et al[50]	2	2	2	2	2	0	0	0	2	NA	NA	12
Giménez et al[51]	2	2	2	2	2	0	0	0	1	NA	NA	11
Giménez et al[52]	2	2	2	2	2	0	0	0	1	NA	NA	11
Gimenéz et al[53]	2	2	2	2	2	0	0	0	2	NA	NA	12
Giménez-Gonzalez et al[54]	2	2	1	2	2	0	0	0	1	NA	NA	10
Gintaute et al[55]	2	2	2	2	2	0	0	0	1	NA	NA	11
Imburgia et al[36]	2	2	2	2	2	0	0	0	1	NA	NA	11
Iturrate et al[16]	2	2	2	2	2	0	1	0	2	NA	NA	13
Iturrate et al[56]	2	2	2	2	2	0	1	0	2	NA	NA	13
Kim et al[43]	2	2	1	2	2	0	1	0	1	NA	NA	11
Mandelli et al[49]	2	2	2	2	2	2	1	0	1	NA	NA	14
Mangano et al[38]	2	2	2	2	2	0	0	0	1	NA	NA	11
Mangano et al[1]	2	2	2	2	2	0	1	0	1	NA	NA	12
Menini et al[57]	2	2	1	2	2	0	2	0	2	NA	NA	13
Miyoshi et al[48]	2	2	2	2	2	0	0	0	2	NA	NA	12
Mizumoto et al[13]	2	2	1	2	2	0	0	0	2	NA	NA	11
Mizumoto et al[44]	2	2	1	2	2	0	0	0	2	NA	NA	11
Moslemion et al[45]	2	2	2	2	2	0	1	2	1	NA	NA	14
Papaspyridakos et al[37]	2	2	2	2	2	0	2	2	2	NA	NA	16
Papaspyridakos et al[46]	2	2	1	2	2	1	1	0	1	NA	NA	12
Rech-Ortega et al[58]	2	2	1	2	0	2	2	0	1	NA	NA	12
Ribeiro et al[18]	2	2	1	2	2	1	1	0	1	NA	NA	12
Tan et al[47]	2	2	1	2	2	0	0	0	1	NA	NA	10
Vandeweghe et al[15]	2	2	1	2	2	0	1	0	1	NA	NA	11

NA, not applicable.

Table 3 Characteristics of the included studies

Study	Study type	Arch; sample size	Number of implants; implant/scan body position (according to FDI notation)	Implant angulation	Implant depth	Implant/analogue system
Andriessen et al[17]	In vivo	Mandible; 25	2; NA	NA	NA	Straumann (Basel, Switzerland)
Alikhasi et al[39]	In vitro	Maxilla; 15	4; 15, 13, 23, 25	13, 23: 0°; 15, 25: 45°	NA	Nobel Biocare (Kloten, Switzerland)
Amin et al[35]	In vitro	Mandible; 10	5; NA	Three median, parallel. Far left 10°, far right 15°	NA	Straumann Bone Level (BL)
Arcuri et al[40]	In vitro	Maxilla; 15	6; 16, 14, 12, 22, 24, 26	16, 12, 22: 0°; 14: 25° (distal); 24: 20° (distal); 26: 20° (distal) and 20° (vestibular)	12, 22, 24, 26: 0 mm; 14: 3 mm; 16: 6 mm	NA
Ciocca et al[41]	In vitro	Mandible; 5	6; 36, 35, 33, 43, 45, 46	NA	NA	Premium Kohno (Sweden & Martina, Due Carrere, Italy)
Di Fiore et al[42]	In vitro	Mandible; 15	6; 46, 44, 42, 32, 34, 36	All parallel	46, 36 placed at 13.0 mm; 44, 34 at 12.8 mm; 42, 32 at 14.0 mm	NA
Giménez et al[50]	In vitro	Maxilla; 5	6; 17, 15, 12, 22, 25, 27	17, 12, 22, 27: 0°; 15: 30° (distal); 25: 30° (mesial)	17, 15, 25, 27: 0 mm; 22: 2 mm; 12: 4 mm	Certain (Zimmer Biomet, Palm Beach Gardens, FL, USA)
Giménez et al[51]	In vitro	Maxilla; 5	6; 17, 15, 12, 22, 25, 27	17, 12, 22, 27: 0°; 15: 30° (distal), 25: 30° (mesial)	17, 15, 25, 27: 0 mm; 22: 2 mm; 12: 4 mm	Certain
Giménez et al[52]	In vitro	Maxilla; 5	6; 17, 15, 12, 22, 25, 27	17, 12, 22, 27: 0°; 15: 30° (distal); 25: 30° (mesial)	17, 15, 25, 27: 0 mm; 22: 2 mm; 12: 4 mm	Certain
Giménez et al[53]	In vitro	Maxilla; 5	6; 17, 15, 12, 22, 25, 27	17, 12, 22, 27: 0°; 15: 30° (distal); 25: 30° (mesial)	17, 15, 25, 27: 0 mm; 22: 2 mm; 12: 4 mm	Certain
Giménez-Gonzalez et al[54]	In vitro	Maxilla; 5	6; 17, 15, 12, 22, 25, 27	17, 12, 22, 27: 0°; 15: 30° (mesial); 25: 30° (distal)	17, 15, 25, 27: 0 mm; 22: 2 mm; 12: 4 mm	Certain
Gintaute et al[55]	In vitro	Mandible; 5	Model 1, 2 implants: 32, 42. Models 2 and 3, 4 implants: 34, 32, 42, 44. Model 4, 6 implants: 36, 34, 32, 42, 44, 46	Models 1, 2 and 4: all parallel; model 3: 2 parallel, 2 straight (40° to 45°)	NA	Certain

	Implant connection; impression level	Number of operators	Scan body	IOS device	Scanning strategy	Modification technique	Risk of bias score
	Internal connection; implant	NA	Straumann	iTero (3.5.0) (Align Technology, San Jose, CA, USA)	Manufacturer's protocol	NA	15
	Internal trilobe, external hexagon; implant	NA	NA	Trios 3	Lingual-buccal-occlusal	NA	13
	Internal connection; implant	NA	Polymer scan body (Regular CrossFit [RC], Straumann)	CEREC Omnicam (4.4.1) (Dentsply Sirona, Charlotte, NC, USA), True Definition (4.1) (3M ESPE, St Paul, MN, USA)	Occlusal-palatal-buccal	NA	14
	Internal hexagon; implant	3	PEEK, titanium, PEEK with titanium base	Trios 3	Occlusal-palatal-buccal	NA	14
	NA; implant	2 experts; 2 with limited experience)	NA	True Definition (5.0.2)	Circular scanning technique	NA	13
	NA; NA	NA	NA	True Definition (5.1.1), Trios 3 (16.4), CEREC Omnicam (4.3.1), 3D Progress (2012-12-19), CS 3500 (2.1.4.10) (Carestream Health, Rochester, NY, USA), CS 3600 (1.2.6) (Carestream Health), Emerald (2018-1) (Planmeca, Helsinki, Finland), Dental Wings (3.7.0.26) (Montreal, Canada)	Manufacturer's protocol	NA	13
	Internal connection; implant	4 (2 experienced, 2 inexperienced)	PEEK	iTero (4.5.0.151)	Stitching halves technique	NA	12
	Internal connection; implant	4 (2 experienced, 2 inexperienced)	PEEK	CEREC Bluecam (4.0) (Dentsply Sirona)	Scan the arch, then scan the scan bodies	NA	11
	Internal connection; implant	4 (2 experienced, 2 inexperienced)	PEEK	Lava COS (0.3.0.2) (3M ESPE)	Circular scanning technique	NA	11
	Internal connection; implant	4 (2 experienced, 2 inexperienced)	PEEK	3D Progress (MHT, Verona, Italy), ZFX IntraScan (Exoscan-mht-2012-12-19) (Zimmer Biomet, Palm Beach Gardens, FL, USA)	Circular scanning technique	NA	12
	Internal connection; implant	4 (2 experienced, 2 inexperienced)	PEEK	True Definition	Circular scanning technique	NA	10
	NA; implant	3	Createch (Createch Medical, Mendaro, Spain)	True Definition (4.0.3.1)	Double gingival scanning method	NA	11

Table 3 (cont.) Characteristics of the included studies

Study	Study type	Arch; sample size	Number of implants; implant/scan body position (according to FDI notation)	Implant angulation	Implant depth	Implant/analogue system
Imburgia et al[36]	In vitro	Maxilla; 5	6; 16, 14, 11, 21, 24, 26	NA	NA	BT Safe Int (BTK-Biotec Implants, Povolaro di Dueville, Italy)
Iturrate et al[16]	In vitro	Maxilla; 10	4; 18, 13, 23, 28	NA	NA	NA
Iturrate et al[56]	In vitro	Maxilla; 10	4; 18, 13, 23, 28	NA	NA	NA
Kim et al[43]	In vitro	Maxilla; 10	6; 16, 14, 12, 22, 24, 26	NA	0 mm (equicrestal level)	IU analogue (Warantec, Seoul, South Korea)
Mandelli et al[49]	In vitro	Maxilla; 10	6; 17, 15, 13, 23, 25, 27	NA	NA	NA
Mangano et al[38]	In vitro	Maxilla; 5	6; 16, 14, 11, 21, 24, 26	NA	NA	BTK (BTK-Biotec Implants)
Mangano et al[1]	In vitro	Maxilla; 10	6; 16, 14, 11, 21, 24, 26	NA	NA	NA
Menini et al[57]	In vitro	Maxilla; 15	4; 16, 13, 23, 26	NA	NA	Low-profile analogues (Zimmer Biomet)
Miyoshi et al[48]	In vitro	Maxilla; 5	6; NA	NA	NA	NobelSpeedy Groovy (Nobel Biocare)
Mizumoto et al[13]	In vitro	Maxilla; 7	4; 16, 13, 23, 26	All parallel	3 mm	TSV 4.1 (Zimmer Biomet)
Mizumoto et al[44]	In vitro	Maxilla; 5	4; 16, 13, 23, 26	All parallel	3 mm	TSV 4.1
Moslemion et al[45]	In vitro	Maxilla; 10	4; 15, 13, 23, 25	13, 23: 0°; 15, 25: 45°	NA	NobelReplace (Nobel Biocare)
Papaspyridakos et al[37]	In vitro	Mandible; 25	4; NA	Anterior: parallel; posterior: 5° (distal)	NA	Abutment-level analogues (Nobel Biocare)
Papaspyridakos et al[46]	In vitro	Mandible; 10	5; between foramen	Three median, parallel. Far left 10°, far right 15°	NA	Straumann BL

	Implant connection; impression level	Number of operators	Scan body	IOS device	Scanning strategy	Modification technique	Risk of bias score
	NA; implant	NA	PEEK	CS 3600 (1.2.6), Trios 3 (16.4), CEREC Omnicam (4.4.4), True Definition (5.1.1)	Zigzag scanning technique	NA	11
	NA; NA	NA	NA	True Definition (5.1.1), Trios 3 (2015-1), iTero (1.5.0.361)	Manufacturer's protocol	Auxiliary geometric device (AGD)	13
	NA; NA	NA	NA	True Definition (5.1.1), Trios 3 (2015-1), iTero (1.5.0.361)	Manufacturer's protocol	AGD	13
	NA; implant	NA	NA	Trios 3	Occlusal-palatal-buccal	NA	11
	Internal connection; implant	NA	NA	True Definition (4.0.3.1)	Stitching halves technique; strategy without stitching halves (occlusal-palatal-buccal)	NA	14
	NA; implant	NA	PEEK	Trios 2 (1.3.3.1), CS 3500 (2.1.4.10), ZFX IntraScan (0.9 RC33 2.8), PlanScan (5-2015) (Planmeca)	Zigzag scanning technique	NA	11
	NA; implant	NA	PEEK	CS 3600 (3.0), Trios 3 (1.6.4), CEREC Omnicam (4.4.4), DWIO (2.1.0.421) (Dental Wings, Montreal, Canada), Emerald (5.1.0)	Zigzag scanning technique	NA	12
	NA; implant	3	Createch	True Definition	Circular scanning technique	NA	13
	NA; abutment	NA	NA	True Definition (5.1.1), CEREC Omnicam (4.3), Trios Scanner 2 (1.3.4.6), CS 3600 (2.1.6.30)	Lingual-occlusal (16 to 26); buccal (26 to 16); turn to lingual side (16)	NA	12
	NA; implant	NA	DESS (Barcelona, Spain)	Trios 3	Stitching or unstitching the palate, occlusal-buccal-palatal	NA	11
	NA; implant	NA	Atlantis Intraoral FLO-IO (Dentsply Sirona), NT (Nt-Trading, Karlsruhe, Germany), DE (DESS), C3D (Core3D Centres, Maartensdijk, Holland), ZI (Zimmer Biomet)	Trios (hardware version unknown)	Occlusal-buccal-palatal	Glass fiduciary markers (GB), pressure-indicating paste (PP), floss tied between scan bodies (FL)	11
	Internal trilobe, external hexagon; implant	NA	DESS, NT-Trading, Doowon (Daejeon, South Korea)	Trios 3 (1.4.7.5)	Lingual-buccal-occlusal	NA	14
	NA; abutment	NA	NA	Trios 3 (1.3.6.3)	Manufacturer's protocol	NA	16
	Internal connection; implant	NA	NA	Trios (hardware version unknown)	Manufacturer's protocol	NA	12

Table 3 (cont.) Characteristics of the included studies

Study	Study type	Arch; sample size	Number of implants; implant/scan body position (according to FDI notation)	Implant angulation	Implant depth	Implant/analogue system
Rech-Ortega et al[58]	In vitro	Simulated arch; 20	6; NA	NA	NA	Certain
Ribeiro et al[18]	In vitro	Maxilla; 10	4; between foramen	Model 1: parallel; model 2: 15° between the more distal implants and 15° between the two central implants	NA	Klockner Implant System (Miami, FL, USA)
Tan et al[47]	In vitro	Maxilla; 5	Model A: 6 implants; 20 mm between implants. Model B: 8 implants; 13 mm between implants	All parallel	NA	Straumann BL
Vandeweghe et al[15]	In vitro	Mandible; 10	6; 36, 34, 32, 42, 44, 46	NA	NA	IBT (Southern Implants, Irene, South Africa)

PEEK, polyetheretherketone.

points and central axis of scan bodies by matching standard cylinders and planes to them. After superimposition of test scans and reference scans, the displacements of the reference points and central axes of scan bodies in the test scans compared with the reference scans were recorded as linear deviations and angular deviations, respectively. In total, 12 studies assessed the linear and angular deviations of DIIs[13,15,39-48].

Another approach involved obtaining the distance and angular deviations between paired scan bodies or implants by measuring the distances and angles between them in test scans and comparing them with the corresponding reference values measured in reference scans. In this method, the test and reference scans were not superimposed. Fifteen studies measured the distance/angular deviations as described above[16,17,42,45,47,49-58].

Accuracy outcomes

Ten studies[18,35,39,43,46-48,55,57,58] took DIIs and CIIs of study models at the same time. All of them were in vitro studies, and no in vivo studies were available. Different CII techniques were used, including splinted[18,35,46-48,57] or non-splinted open tray[18,39,46,55,57], splinted[43] or non-splinted pickup[58] and closed tray[18,39,57]. Of the 10 studies, seven directly compared the accuracy of DIIs and CIIs, of which five found DIIs more accurate than or comparable to CIIs[18,35,39,46,57], whereas two found that CIIs taken using a splinted open tray technique were more accurate than DIIs[43,47].

Considering 100 μm and 0.4 degrees as clinically acceptable levels of deviation[17], most studies reported linear/distance/3D deviations above 100 μm and angular deviations above 0.4 degrees and therefore too great for clinical application.

The in vivo study reported a mean distance deviation of 226 μm and a mean angular deviation of 2.582 degrees by assessing the accuracy of intraoral scans of 25 edentulous mandibles with two implants[17]. Four of the 25 scans were not able to stitch the images together and could not be used.

For in vitro studies, the trueness of DIIs ranged from 7.6 to 731.7 μm and angular deviations ranged from 0.13 to 10.01 degrees. Twelve studies reported linear/distance/3D deviations below 100 μm[1,18,35,37,41,46,49,50,52,54,55,57]

	Implant connection; impression level	Number of operators	Scan body	IOS device	Scanning strategy	Modification technique	Risk of bias score
	Internal hex; implant	NA	Core3D Centres	True Definition	NA	NA	12
	NA; implant	NA	NA	True Definition	Manufacturer's protocol	NA	12
	NA; implant	NA	Core3D Centres	True Definition, Trios (hardware version unknown)	Capture each scan body and then move forward	NA	10
	External connection; implant	NA	PEEK	Lava COS, True Definition, CEREC Omnicam, Trios (hardware version unknown)	Manufacturer's protocol	NA	11

and two reported angular deviations below 0.4 degrees[55,57]. Eight studies reported errors larger than 200 μm[13,38,42-45,47,53]. Precision of DIIs was investigated in seven studies[1,15,16,36,38,48,56] and ranged between 15.2 and 204.2 μm.

The wide range of accuracy outcomes was mainly attributed to the different methodologies and study characteristics of the included studies, such as the IOS and scan body selected, operator experience, scanning strategy and modification techniques used, and the implant connection, depth, angulation and interimplant distance in the study models. These variables are further summarised in this systematic review. A detailed description of the accuracy outcomes of DIIs is provided in Tables 4 and 5.

Interimplant distance

The effect of interimplant distance on the accuracy of DIIs was evaluated in two studies[42,47]. The effects of scanning sequence[50,51,53,54], range[48], length of the arch scanned[41] and implant position[13] were summarised along with interimplant distance, based on the same hypothesis that larger stitching errors could occur with increasing scanning distance since IOSs generate consecutive 3D images by superimposing one image on another. The results obtained by these studies were mainly consistent with the expectation that errors would increase as scanning distance or interimplant distance increased[41,42,47,48], or that the first scanned quadrant would be more accurate than the second[50,51,53,54], except for one study that reported greater deviations with the first scanned implant[13].

Implant angulation, depth and connection

Ten studies examined the effect of implant angulation of 10 to 15 degrees[18,46], 30 degrees[50-54] and 40 to 45 degrees[39,45,55]. Seven of these found that angulation was irrelevant to the accuracy of DIIs[39,46,50-54]. Two studies found that angulated implants resulted in lower accuracy than parallel implants[18,55], and one reported that implant angulation had a positive or negative effect on the accuracy of DIIs depending on the connection and scan body type used[45].

Five in vitro studies examined the effect of implant depth[50-54]. One study reported lower

Table 4 Accuracy outcomes of studies taking both DIIs and CIIs

Study	Methods of accuracy measurement	Evaluated variables	DII accuracy outcomes (tooth numbering given according to FDI notation)
Alikhasi et al[39]	Linear and angular deviations	Implant connection and angulation	Internal connection: Straight: 188 µm, 0.585°; Tilted: 162 µm, 0.364° External connection: Straight: 195 µm, 0.587°; Tilted: 165 µm, 0.366°
Amin et al[35]	3D overall deviations	IOS brand	Omnicam: 46.41 µm True Definition: 19.32 µm
Gintaute et al[55]	Linear and angular deviations	Implant angulation	Model 1: 18.47 µm, 0.04° Model 2: 9.48 µm, 0.17° Model 3: 35.78 µm, 0.22° Model 4: 31.11 µm, 0.24°
Kim et al[43]	Linear and angular deviations	NA	16: 127.7 µm 14: 158.1 µm 22: 172.4 µm 24: 216.8 µm 26: 472.7 µm Overall: 177.4 µm Angular deviations in XY and ZX planes: 16: 0.25°, 0.32° 14: 1.38°, 0.34° 12: 0.70°, 0.34° 22: 0.49°, 0.22° 24: 2.61°, 1.08° 26: 10.01°, 0.87°
Menini et al[57]	Distance/angular deviations between paired scan bodies	NA	12 µm, 0.257°
Miyoshi et al[48]	Linear deviations	Scanning range	The precision of DIIs declined as the impression ranges expanded
Papaspyridakos et al[46]	Linear deviations	Implant angulation	Implant 1: 23.39 µm Implant 2: NA Implant 3: 15.27 µm Implant 4: 7.60 µm Implant 5: 29.02 µm Overall: 19.38 µm
Rech-Ortega et al[58]	Distance deviations between paired scan bodies	NA	Linear deviation of different reference distances: 23–123 µm
Ribeiro et al[18]	3D overall deviations	Implant angulation	3D deviations in X, Y and Z axes: Model 1 (parallel): X, 15 µm; Y, 17 µm; Z, 15 µm; model 2 (non-parallel): X, 32 µm; Y, 22 µm; Z, 32 µm
Tan et al[47]	Linear, angular and distance deviations between paired scan bodies	Interimplant distances	Linear deviations: Model A (6 implants): 36.3–172.5 µm (Trios); 291.6–731.7 µm (True Definition) Model B (8 implants): 40.2–148.0 µm (Trios); 160.9–620.2 µm (True Definition) Angular deviations in X axis, angular deviations in Y axis, distance deviations: Model A (6 implants): −2.189°–0.306°/−0.932°–0.215°, 13.3–166.8 µm (Trios); −2.249°–−0.037°/−0.715°–0.469°, −709.2–−267.5 µm (True Definition) Model B (8 implants): −0.476°–0.532°/−0.812°–0.377°, −9.1–69.8 µm (Trios); −0.688°–0.511°/−1.052°–0.706°, −602.5–−151.1 µm (True Definition)

ext, external connection; int, internal connection.

	CII accuracy outcomes (tooth numbering given according to FDI notation)	Conclusions
	Direct CIIs: Internal/straight: 0.280 µm, 2.287°; Internal/tilted: 0.389 µm, 4.765°; External/straight: 0.711 µm, 1.004°; External/tilted: 0.364 µm, 1.098° Indirect CIIs: Internal/straight: 0.885 µm, 4.096°; Internal/tilted: 0.721 µm, 9.371°; External/straight: 0.797 µm, 4.851°; External/tilted: 0.442 µm, 2.062°	DIIs were more accurate than CIIs. The type of connection and implant angulation had no effect
	Splinted open tray: 167.93 µm	DIIs were more accurate than CIIs
	Non-splinted open tray, polyether/vinyl polysiloxane: Model 1: 14.27/11.04 µm, 0.03/0.07° Model 2: 12.22/12.74 µm, 0.07/0.08° Model 3: 19.78/4.87 µm, 0.04/0.16° Model 4: 44.03/16.86 µm, 0.15/0.06°	The accuracy of DIIs and CIIs seems to be clinically acceptable. Angulated implants showed lower accuracy than parallel implants
	Splinted pickup: 16: 56.2 µm, 6.44°, 0.47°; 14: 39.9 µm, 0.92°, 0.21°; 12: 0.10°, 0.23°; 22: 52.9 µm, 0.22°, 0.23°; 24: 85.9 µm, 0.83°, 0.17°; 26: 110.4 µm, 4.22°, 0.23° Overall: 72.2 µm	CIIs showed significantly better trueness and precision than DIIs for overall angular deviations in X, Y, Z and D. Differences in angular deviations were small (< 1°) between CIIs and DIIs
	7 different techniques. Distance error: 10––60 µm Angle error: 0.110°–0.536°	DIIs were more accurate than CIIs
	Splinted open tray: the same trend was found with CIIs	DIIs should be limited to small prostheses, such as 3-unit superstructures supported by two implants. The precision of DIIs and CIIs declined as the impression ranges expanded
	Splinted implant level: 7.42 µm Non-splinted implant level: 17.65 µm Splinted abutment level: 13.05 µm Non-splinted abutment level: 8.23 µm	No significant difference was found between DIIs and master casts. The accuracy of DIIs was not different from the splinted CII, and both were more accurate than the non-splinted CII. Implant angulation of 10° and 15° showed no effect
	Pickup: 20–123 µm	Linear deviation of DIIs and CIIs were within the acceptable range (150 µm) for clinical application
	Closed tray, non-splinted open tray, splinted open tray: Model 1 (parallel): X, 20–36; Y, 22–36; Z, 11–26 Model 2 (non-parallel): X, 17–26; Y, 15–21; Z, 15–24	For parallel implants, DIIs were more accurate than CIIs. For non-parallel implants, DIIs and CIIs yielded similar results. Parallel implants showed better accuracy compared to non-parallel implants
	Splinted open tray: Model A (6 implants): 10.9–24.6 µm Model B (8 implants): 16.3–39.3 µm	CIIs exhibited lowest or second-lowest global linear deviations, and DIIs by True Definition exhibited the poorest accuracy. Reducing interimplant distances may decrease global linear deviations of DIIs

Table 5 Accuracy outcomes for DIIs in edentulous arches (studies already listed in Table 4 were not listed again)

Study	Study type	Methods of accuracy measurement	Evaluated variables	DII accuracy outcomes (tooth numbering given according to FDI notation)	Conclusions
Andriessen et al[17]	In vivo	Distance/angular deviations between paired scan bodies	NA	226 µm (21–638 µm), 2.582° (0.123°–9.563°)	The linear and angular deviation of DIIs were too large to produce a well-fitting superstructure on 2 implants in an edentulous mandible
Arcuri et al[40]	In vitro	Linear and angular deviations	Scan body material and position, operator experience	PEEK: 54.7 µm Ti: 99.2 µm PEEK with Ti: 196.4 µm 16: 117 µm 14: 126 µm 12: 100 µm 22: 81 µm 24: 104 µm 26: 172 µm PEEK: 0.6423° Ti: 0.7137° PEEK with Ti: 0.7600° 16: 0.6778° 14: 0.7352° 12: 0.7810° 22: 0.8681° 24: 0.4625° 26: 0.7075°	Scan body material with PEEK showed the best accuracy, followed by Ti, with PEEK-Ti showing the lowest accuracy. Implant angulation affected the linear deviations. Operator experience had no significant effect on IOS accuracy. 22 showed the best accuracy and 26 the worst
Ciocca et al[41]	In vitro	Linear deviations	Operator experience, length of arch scanned	36: 86 µm 35: 47 µm 33: 77 µm 43: 48 µm 45: 44 µm 46: 76 µm	DIIs showed a clinically acceptable level of accuracy. Operator experience showed no significant effect. Errors increased as the length of the arch scanned increased
Di Fiore et al[42]	In vitro	Linear and distance deviations between paired scan bodies	IOS brand, distance between scan bodies	True Definition (31 µm) > Trios (32 µm) > CS 3600 (61 µm) > Omnicam (71 µm) > Emerald (101 µm) > CS 3500 (107 µm) > Dental Wings (148 µm) > 3D Progress (344 µm). True Definition and CS 3600 showed a linear relationship between distance errors and distance between scan bodies	Some IOSs cannot be used to take DIIs for edentulous patients. True Definition and CS 3600 showed a linear relationship between distance errors and distance between scan bodies
Giménez et al[50]	In vitro	Distance deviations between paired scan bodies	Implant angulation and depth, operator experience, implant distance (scanning sequence)	27–25: –14.3 µm 27–22: –16.2 µm 27–12: –27.9 µm 27–15: –23.1 µm 27–17: –32.0 µm	DIIs were not accurate enough for multiple-unit reconstructions according to conventional standards. Implant angulation and depth and operator experience showed no significant effect. The first quadrant was significantly more accurate than the second
Giménez et al[51]	In vitro	Distance deviations between paired scan bodies	Same as Giménez et al[50]	27–25: –28.49 µm 27–22: –22.46 µm 27–12: –107.25 µm 27–15: 116.84 µm 27–17: –123.09 µm	Angulation and implant depth showed no significant effect. Inexperienced operators performed with higher accuracy. The first quadrant was significantly more accurate than the second

Table 5 (cont.) Accuracy outcomes for DIIs in edentulous arches (studies already listed in Table 4 were not listed again)

Study	Study type	Methods of accuracy measurement	Evaluated variables	DII accuracy outcomes (tooth numbering given according to FDI notation)	Conclusions
Giménez et al[52]	In vitro	Distance deviations between paired scan bodies	Implant angulation and depth, operator experience, number of trials	Experienced: –45.02––11.02 µm Inexperienced: –6.07–39.70 µm Angulated implants: –20.2 µm Normal implants: –37.9 µm	Angulation and implant depth had no significant effect. Experienced operators delivered more accurate DIIs. Inexperienced operators increased in as the number of trials increased
Giménez et al[53]	In vitro	Distance deviations between paired scan bodies	Same as Giménez et al[50]	ZFX IntraScan: –32.7––216.7 µm 3D Progress: 9.3–497.4 µm Angulated implants: –125 µm Straight implants: –150 µm	Operator experience, implant angulation and depth showed no significant effect. ZFX IntraScan and 3D Progress were not accurate enough for multi-implant impressions. The first quadrant was more accurate than the second
Giménez-Gonzalez et al[54]	In vitro	Distance/angular deviations between paired scan bodies	Same as Giménez et al[50]	27–25: 5.38 µm 27–22: 9.86 µm 27–12: 10.05 µm 27–15: –14.07 µm 27–17: –26.97 µm 27–25: 0.16° 27–22: 0.40° 27–12: 0.43° 27–15: 0.09° 27–17: 0.12°	Implants placed subgingivally showed lower accuracy than those placed gingivally. Experienced operators performed significantly better for distance deviations. Implant angulation showed no effect. The accuracy of True Definition was within clinically acceptable limits. The first quadrant was significantly more accurate than the second
Imburgia et al[36]	In vitro	3D overall deviations	IOS brand	Trueness: CS 3600 (60.6 µm) > Omnicam (66.4 µm) > Trios 3 (67.2 µm) > True Definition (106.4 µm) Precision: Trios 3 (31.5 µm) > Omnicam (57.2 µm) > CS 3600 (65.5 µm) > True Definition (75.3 µm)	Significant differences in trueness were found among different IOSs. No significant differences in precision were found among different IOSs
Iturrate et al[56]	In vitro	Distance deviations between paired scan bodies	AGD	With AGD (from shortest to largest reference distance): Trueness: 11–64 µm Precision: 7–63 µm Without AGD: Trueness: 21–125 µm Precision: 18–84 µm	Use of an AGD enabled IOSs to obtain more accurate digital scans. Trueness decreased as reference distance increased
Iturrate et al[16]	In vitro	Distance deviations between paired scan bodies	AGD	With AGD (from shortest to largest reference distance): Trueness: 8–83 µm Precision: 7–83 µm Without AGD: Trueness: 17–189 µm Precision: 14–118 µm	AGD showed significantly better trueness and precision
Mandelli et al[49]	In vitro	Distance deviations between paired scan bodies	Scanning strategy	Stitching: 44.2 µm No stitching: 55.5 µm	Stitching showed better accuracy compared to no stitching. There was a significant positive correlation between errors and reference length

Table 5 (cont.) Accuracy outcomes for DIIs in edentulous arches (studies already listed in Table 4 were not listed again)

Study	Study type	Methods of accuracy measurement	Evaluated variables	DII accuracy outcomes (tooth numbering given according to FDI notation)	Conclusions
Mangano et al[38]	In vitro	3D overall deviations	IOS brand	Trueness: CS 3500 (63.2 µm) > Trios (71.6 µm) > ZFX IntraScan (103.0 µm) > PlanScan (253.4 µm) Precision: CS 3500 (55.2 µm) > Trios (67.0 µm) > ZFX IntraScan (112.4 µm) > PlanScan (204.2 µm)	The accuracy of the investigated IOSs differed significantly
Mangano et al[1]	In vitro	3D overall deviations	IOS brand	Trueness: CS 3600 (44.9 µm) > Trios 3 (46.3 µm) > Emerald (66.3 µm) > Omnicam (70.4 µm) > DWIO (92.1 µm) Precision: Trios (15.2 µm) > CS 3600 (35.7 µm) > Emerald (61.5 µm) > Omnicam (89.3 µm) > DWIO (111 µm)	The accuracy of the investigated IOSs differed significantly
Mizumoto et al[13]	In vitro	Linear and angular deviations	Scanning strategy (stitching or unstitching the palate), implant position	Linear deviations for stitching and unstitching: 16: 114.57 µm, 120.94 µm; 0.21°, 0.34° 13: 89.42 µm, 115.83 µm; 0.36°, 0.48° 23: 170.51 µm, 198.0 µm; 0.39°, 0.48° 26: 196.2 µm, 206.28 µm; 0.68°, 0.78° Overall: 142.7 µm, 160.3 µm; 0.41°, 0.52°	Stitching and unstitching the palate showed no significant difference. Implant position had a significant effect on trueness
Mizumoto et al[44]	In vitro	Linear and angular deviations	Scanning techniques, scan bodies	All scan bodies and scan techniques resulted in a distance deviation greater than 170 µm and an angular deviation greater than 0.5°	The scan body and scan technique had an effect on accuracy. The ZI scan body showed better accuracy. Splinting scan bodies with floss showed lower accuracy than GB, PP and no modification technique
Moslemion et al[45]	In vitro	Linear, angular and distance deviations between paired scan bodies	Implant connection and angulation, scan body type and shape	External (straight/angled) DESS: 0.2 mm/0.22 mm, 0.32°/0.26°, 0.08 mm/0.11 mm NT-Trading: 0.09 mm/0.08 mm, 0.36°/0.27°, 0.03 mm/0.05 mm Doowon: 0.07 mm/0.08 mm, 0.28°/0.13°, 0.03 mm/0.02 mm Internal (straight/angled) DESS: 0.17 mm/0.13 mm, 0.47°/0.43°, 0.13 mm/0.09 mm NT-Trading: 0.06 mm/0.07 mm, 0.35°/0.25°, 0.04 mm/0.04 mm Doowon: 0.05 mm/0.07 mm, 0.52°/0.56°, 0.02 mm/0.04 mm	DESS had more linear deviation compared with other scan bodies. Internal and external connection only showed a significant difference with the DESS scan body. Implant angulation had different effects on the accuracy depending on the connection and scan body type used
Papaspyridakos et al[37]	In vitro	3D overall deviations	NA	Printed casts: 59 ± 16 µm	The accuracy of the printed casts from DIIs was clinically acceptable
Vandeweghe et al[15]	In vitro	3D overall deviations	IOS brand	Trueness: Trios (28 µm) > True Definition (35 µm) > Omnicam (61 µm) > Lava COS (112 µm) Precision: True Definition (30 µm) > Trios (33 µm) > Omnicam (59 µm) > Lava COS (66 µm)	There was a significant difference in accuracy between the different IOSs. Lava COS lacked the necessary accuracy for large-span DIIs. The other 3 IOSs demonstrated an acceptable level of accuracy

accuracy for implants placed subgingivally compared with those placed gingivally[54], whereas the remaining four found that implant depth had no significant effect.

Regarding implant connection, one study recorded no effect[39], and another reported that internal and external connection only displayed a significant difference with a certain scan body type (DESS, Barcelona, Spain)[45].

Operator experience

The effect of operator experience was investigated in six studies[41,50-54]. Three of these reported that operator experience had no significant effect[41,50,53]. Two of these studies, which used the Lava Chairside Oral Scanner (Lava COS, 3M ESPE, St Paul, MN, USA) and True Definition scanner (3M ESPE), reported better accuracy with experienced operators[52,54], whereas a study using CEREC Bluecam (Dentsply Sirona, Charlotte, NC, USA) found that DIIs were more accurate when taken by inexperienced operators[51].

Scan body type

Three studies examined the effect of scan body type and the significant reported effects of scan bodies on the accuracy of DIIs[40,44,45]. One found that polyetheretherketone (PEEK) scan bodies had the best accuracy, followed by titanium, whereas PEEK with a titanium base showed the worst accuracy[40]. The other two investigated scan bodies from different brands[44,45]. Although one study found that Zimmer Biomet (Palm Beach Gardens, FL, USA) scan bodies had the best accuracy compared with Atlantis Intraoral FLO-IO (Dentsply Sirona), Nt-Trading (Karlsruhe, Germany), DESS and Core3D Centres (Maartensdijk, Holland) scan bodies[44], the other found that DESS scan bodies displayed more linear deviations than Nt-Trading and Doowon (Daejeon, South Korea) scan bodies[45]. For other studies, Createch (Mendaro, Spain)[50-55,57], DESS[13,39], Core3D Centres[47,58], TruScan (TruAbutment Korea, Seoul, South Korea)[43], MegaGen (Daegu, South Korea)[1] and ProScan (Cincinnati, OH, USA)[15] scan bodies and the original scan bodies matched with implant systems like Straumann (Basel, Switzerland) and Nobel Biocare (Kloten, Switzerland)[35-37,46,48,49] were used. The remaining studies did not clearly state the scan bodies used.

IOS type

Six in vitro studies compared the accuracy of different IOSs for DIIs by calculating the 3D deviations of test scans, and all reported that IOS type had a significant effect[1,15,35,36,38,42]. The IOSs investigated included True Definition, Trios (3Shape, Copenhagen, Denmark), CEREC Omnicam (Dentsply Sirona), 3D Progress (MHT, Verona, Italy), CS 3500 (Carestream Health, Rochester, NY, USA), CS 3600 (Carestream Health), Emerald (Planmeca, Helsinki, Finland), DWIO (Dental Wings, Montreal, Canada), ZFX IntraScan (Zimmer Biomet), PlanScan (Planmeca) and Lava COS. Trios, CS 3600 and CEREC Omnicam showed an overall deviation lower than 100 µm in all of the available studies, while PlanScan and 3D Progress showed errors larger than 250 µm, indicating unreliable accuracy (Fig 3). The specific data regarding the accuracy of different IOSs and software versions are displayed in Tables 4 and 5.

Scanning strategy and modification techniques

For in vitro studies, one study compared the scanning strategy with and without stitching the two halves and found that the stitching strategy showed better accuracy[49]. Another study found no difference between the techniques involving stitching or unstitching of the palate[13].

The common scanning strategies adopted were as follows:

- scanning the occlusal, palatal/lingual and buccal surfaces from one end of the arch to the contralateral side[13,35,40,43,44,49], or in the sequence of lingual, buccal and occlusal surface (occlusal-lingual-buccal/lingual-buccal-occlusal technique)[39,45];
- continuous circular scanning around each scan body from one end to the other (circular scanning technique)[41,52,53,57];

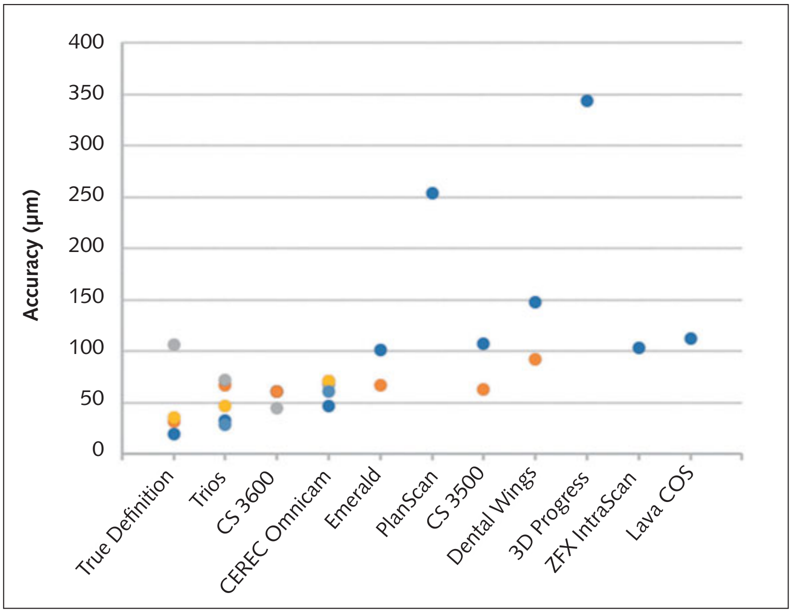

Fig 3 Accuracy outcomes for different IOS devices.

- scanning from one end to the anterior site, repeating the process with the other half and merging the two halves together (merging halves technique)[49,50];
- scanning in an arc movement from the vestibular to palatal area and back, and slowly moving forward (zigzag scanning technique)[1,36,38].

Other studies employed other techniques[37,55] or simply followed the manufacturer's protocol[15,16,18,42,46,56].

Modification techniques were applied in three in vitro studies[16,44,56]. Two studies reported that wearing an auxiliary geometric device (AGD) significantly improved the accuracy of digital scans[16,56]. The other study used glass fiduciary markers, pressure-indicating paste and floss to facilitate the process of taking DIIs of edentulous arches, and reported that splinting scan bodies with floss showed the worst accuracy[44].

Discussion

The present systematic review aimed to evaluate the accuracy of full-arch DIIs taken using IOSs and summarise the related variables. Twenty-nine of the included studies were in vitro, and only one in vivo study was available. The possible effect of implant connection, angulation and depth, IOS type, scan body type, length of the arch scanned, operator experience and modification technique (such as AGD and splinting) were analysed.

Accuracy outcomes

Only one in vivo study was included in this systematic review. Clinical studies of the accuracy of DIIs in edentulous arches are currently scarce. This is primarily because, unlike in vitro studies with the help of CMMs and laboratory scanners, the actual value of the reference distance/angle or the 3D position of the scan body cannot be measured directly in vivo, meaning the exact deviations of DIIs cannot be obtained to assess accuracy.

The only in vivo study, conducted by Andriessen et al[17], managed to quantitatively assess the accuracy of DIIs. The researchers recruited 25 participants with mandibular complete overdenture supported by two implants and took DIIs. The original definitive casts were used as reference casts based on the theory that implants would migrate to the best fit position on the bar with an immediate loading protocol, i.e., that they would osseointegrate into the same position of the analogues in the cast on which the bar was fabricated. However, this theory was derived from an animal experiment and lacked reliability[59]. Andriessen et al[17] reported a mean linear deviation of 226 µm and an angular deviation of 2.582 degrees for DIIs in clinical situations. Only five of the 25 scans they took were within the clinically acceptable range of error[17].

A number of other in vivo studies were not included in this systematic review; they investigated the accuracy of the restoration from DIIs and CIIs by observing the voids at the bar–implant connection on radiographs[29,30]. However, these results contained errors relating to pouring casts and restoration/framework fabrication. New methodologies to assess the accuracy of DIIs in clinical settings need to be developed and applied in more in vivo studies.

Seven in vitro studies comparing the accuracy of DII and CII achieved opposing conclusions[18,35,39,43,46,47,57]. While five studies reported that the accuracy of DIIs was superior or comparable to that of CIIs, Kim et al[43] found that Trios exhibited a significantly higher linear deviation (177.4 µm) than the splinted pickup impression technique (72.2 µm), and Tan et al[47] recorded better accuracy in all implant positions with the splinted open tray technique compared with Trios and True Definition. This diversity was likely caused by wide differences in study design, evaluation methods and devices selected.

Most of the in vitro studies reported a mean linear/distance/3D deviation greater than 100 µm in different conditions[13,16,38-40,42-45,47,53], which was defined as the threshold of clinically acceptable misfit[17] and commonly applied. Other studies found a deviation below 100 µm[1,18,35,37,41,46,49,50,52,54,55,57] but did not fabricate physical models or frameworks from DIIs, except for one study[37]. Since the model-free process of full-arch rehabilitation has not been generally applied in clinical practice, deviations are expected to increase and exceed 100 µm if other necessary working steps are included. In addition, clinical factors such as mucosa mobility, saliva, oral humidity and tongue movements that were not included in bench studies could double the errors in DIIs taken in the oral cavity[60].

The present systematic review thus revealed that the results of most studies suggested that the errors in DIIs taken in fully edentulous arches were too large for clinical application. This finding contradicts the conclusion of a previous systematic review on the acceptable accuracy of IOSs for in vitro studies[61]. This inconsistency could be attributed to the different thresholds adopted for the clinically acceptable level of misfit. Wulfman et al[61] considered deviations below 150 µm as clinically acceptable; this value was originally defined by Jemt[62] based on clinical experience. In contrast, the present authors adopted 100 µm as the threshold in line with the hypothesis proposed by Andriessen et al[17]. However, the overall high risk of bias of the included studies supported the conclusions drawn by Flügge et al[6] relating to the low level of evidence of the available data for accuracy of DIIs and CIIs.

Related variables

The studies agreed that the errors in DIIs increased as interimplant distance also increased[42,47], mainly owing to the working principles of IOSs. Specifically, IOSs stitch the newly captured images to the previous ones using a best fit algorithm to achieve optimal overlapping of images, and the errors continue to accumulate as scanning distance increases[13]. The accumulated errors are maximised in fully edentulous arches due to the lack of anatomical landmarks in long-distance stitching[17]. A shorter length of the arch scanned[41], a smaller scanning range[48] and the first scanned quadrant[50,51,53,54] showed better accuracy for DIIs in other studies for the same reason. The only exception was the study by Mizumoto et al[13] which showed higher distance deviations at the starting position for scanning; this contradicting result may stem from the differences in scanning technologies (confocal microscopy was used in the study), algorithm correction and scanning protocols.

Most studies found that implant angulation, depth and connection were irrelevant to the accuracy of DIIs in fully edentulous arches. It should however be noted that five of ten studies analysing the effect of implant angulation and all five studies assessing the effect of implant depth were conducted by the same research group and used an identical study design except for the IOS device[50-54], which could cause great bias. Thus, the effect of implant angulation and depth should be studied further using a more comparable assessment method.

Five of six articles examining the effect of operator experience also used the same study design[50-54]. The effect of operator experience varied with the use of different IOSs. When using iTero (Align Technology, San Jose, CA, USA), 3D Progress and ZFX IntraScan, operator experience had no significant effect[50,53], whereas with Lava COS and True Definition, experienced operators achieved better accuracy[52]. However, Ciocca et al[41] found that operator experience had no impact with True Definition. When using CEREC Bluecam, an inexperienced operator who had only previously taken one impression showed higher accuracy, most likely due to a different way of positioning the scanner tip[51].

Scan body type was also found to affect accuracy. Arcuri et al[40] focused on the influence of scan body materials and recorded significantly higher accuracy with PEEK (54.7 µm) than with titanium (99.2 µm) and hybrid materials (PEEK scan region with a titanium base; 196.4 µm). Since the optical properties of the scanned materials were known to affect the accuracy of scans[63], Arcuri et al[40] assumed that the IOS could capture more points on the PEEK surface than on the more reflective airborne-particle-abraded surface. The mismatch between the two components of the hybrid scan bodies might also lead to inferior accuracy. Mizumoto et al[44] found that a Zimmer Biomet scan body with a shorter and simpler shape and fewer undercuts showed better accuracy and had a shorter scanning time than others, implying that shorter and simpler scan bodies might improve the scanning process. Moslemion et al[45] also reported higher deviations for DESS scan bodies due to their greater height, whereas Flügge et al[19] reported lower precision with shorter scan bodies. The effects of scan body design and materials should be studied further.

IOS type significantly affected the accuracy of DIIs in all six related studies[1,15,35,36,38,42]. The working principles of popular IOSs include confocal microscopy (Trios and ZFX IntraScan), active wavefront sampling technology (True Definition), active triangulation technology (CEREC Omnicam) and parallel confocal laser technology (iTero). Notably, the accuracy of DIIs improved greatly with newer IOSs; for example, Emerald, Omnicam and True Definition represent the new generation of PlanScan, CEREC Bluecam and Lava COS, respectively.

Various scanning strategies were used in the different studies, but only one investigated the impact of scanning strategy on the accuracy of DIIs in fully edentulous arches[64]. Mandelli et al[49] found that scanning the separate halves and stitching them together showed better accuracy than continuously scanning from side to side (44.2 µm compared with 55.5 µm). The scanning strategies could be roughly divided into four categories, namely the occlusal-palatal-lingual path, circular scanning, merging halves and the zigzag technique. Future studies should evaluate the effects of use of different scanning strategies.

Different modification techniques were developed to improve the accuracy of stitching, mainly by discovering or adding landmarks during scanning. However, Mizumoto et al[44] compared the scanning techniques of glass fiduciary markers (GB), pressure-indicating paste (PP) and splinting with floss (FL) with the unmodified master model (NO) in vitro and found that FL showed significantly lower accuracy than NO, GB and PP. The authors inferred that the direct contact between the floss and the scan body's scanning area might hamper digitisation with scan bodies. However, the scan bodies were partially in traction when connected by floss, which may have resulted in higher deviations. Compared with NO, GB and PP had no significant effect, which contradicted a previous finding that the artificial landmark in the edentulous space of a partially edentulous model could improve IOS accuracy[65].

Based on the theory that geometry with different curvature facilitates the best fit alignment, Iturrate et al[16,56] invented an AGD to be worn during intraoral scanning to simulate the natural dentition; they found that AGD significantly improved scanning accuracy. For DIIs of maxillae, the palatal rugae were expected to have a positive effect on accuracy due to their stable and bumpy shape; however, Mizumoto et al[13] found that scanning or not scanning the palate while taking DIIs had no significant impact on their accuracy.

The main limitations of this systematic review relate to the limited number of in vivo studies and the diverse range of methodologies of the included studies. Thus, for future research, more in vivo studies investigating the accuracy of DIIs in fully edentulous arches are encouraged. It is also important to develop new methodologies for assessing the accuracy of impressions intraorally. Future in vitro studies should evaluate the effects of scanning strategy and scan body type on the accuracy of DIIs in fully edentulous arches, and new modification techniques should be developed.

Conclusions

Based on the results of most of the included studies, full-arch DIIs taken using IOSs are not sufficiently accurate for clinical application. The accuracy of DIIs in fully edentulous arches varies greatly depending on interimplant distance, scan body type, IOS type and operator experience. Implant angulation, connection and depth do not affect the accuracy of full-arch DIIs. The effects of different scanning strategies and modification techniques are still unclear and need further investigation.

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