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Accuracy of Fixed Implant-Supported Dental Prostheses Additively Manufactured by Metal, Ceramic, or Polymer: A Systematic Review

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Abstract

Purpose: Additive manufacturing (AM) in prosthodontics is used as an alternative to casting or milling. Various techniques and materials are available for the additive manufacturing of the fixed and removable tooth-supported restorations, but there is a lack of evidence on the accuracy of AM fixed implant-supported prostheses. Recent studies investigated the accuracy of ceramic AM prostheses. Therefore, the aim of this systematic review was to evaluate the accuracy of additively manufactured metal, ceramic or polymers, and screw- or cement-retained fixed implant-supported prostheses.

Materials and Methods: Two calibrated investigators performed an electronic search of relevant publications in the English language following selected PICOS criteria and using a well-defined search strategy (latest search date—1st of June, 2021). Based on the exclusion criteria (no control group, less than five samples per group, 3D printing of the implant abutment part, only subjective evaluation of accuracy, etc.) studies were not included in the review. Quantitative data of accuracy evaluation such as marginal gap, strain analysis, and linear measurements was extracted and interpreted. QUADAS-2 tool was used to assess the risk of methodological bias of all included studies.

Results: Sixteen in vitro studies were selected for the final analysis. Six of the selected studies evaluated screw-retained restorations and 10 cement-retained implant-supported restorations. Only 4 publications concluded that AM restorations were more accurate than conventionally made (cast or milled) ones. The most common finding was that AM restorations were more accurate than cast and demonstrated less or similar accuracy compared to milled ones (n = 10 studies). Detected marginal discrepancies mean values of the AM prosthesis varied from 23 to more than 200 μm, but most of them were categorized as clinically acceptable.

Conclusions: AM implant-supported fixed prostheses demonstrate similar accuracy compared to conventional and computer-aided design and computer-aided manufacturing techniques in vitro. Detected inaccuracies of AM restorations do not exceed clinically acceptable limits. Clinical studies with longer follow-up periods are needed to show the reliability of AM prostheses.

To date, there are mainly three different methods to manufacture implant-supported dental prostheses: casting, subtractive manufacturing, and additive manufacturing. In the subtractive method, computer numerical control (CNC) milling machines drill and cut a block of solid material to fabricate the prosthesis.[1] Additive manufacturing (AM), also known as 3D printing or rapid prototyping, builds objects layer by layer.[2] AM, when compared to subtractive techniques, produces less waste material and is not limited to the diameter of burs.[1]

The AM implant-supported dental prosthesis can be produced from metals, ceramics, and polymers.[3] All materials for intraoral use need to be biocompatible and have sufficient mechanical properties. The exact composition of AM material may vary depending on the manufacturer which affects the properties of the AM product.[3–5] For AM of metal, titanium (Ti, e.g., Ti_6Al_4V) and cobalt chromium (CoCr) alloys in powder consistency are used most often. CoCr powders might include molybdenum, tungsten, silicon, cerium, iron, manganese, and carbon.[5] Superior esthetics, biocompatibility and wear resistance of prosthesis might be achieved by AM of zirconia and aluminum oxide ceramics.[6,7] As AM of polymers produces prosthesis of lower mechanical properties, it is especially useful for the fabrication of interim and removable prostheses.[3,8]

As for AM of metal dental prostheses, the most commonly used are powder bed fusion (PBF) technologies: selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM).[9,10] To solidify the layers of powder material, EBM employs an electron beam, while other technologies (SLM, SLS, DMLS) use lasers.[5,11,12] When compared to SLM, SLS produces partially melted and porous objects. However, SLM induces internal stresses within the object which then requires additional heat treatment.[5] Confusion arises between DMLS and SLM since both terms are used interchangeably to explain the same basic AM technology which fully melts the particles.[5] However, the studies that were included in the current systematic review have used both terms. Therefore, they were analyzed separately. When fabricating screw-retained implant-supported prosthesis, a combination of additive and subtractive technologies have been described in which the implant-abutment interface is overbuilt purposely with AM techniques and posteriorly geometries are reached with milling methods.[9,13]

Accurate digital or conventional impressions are required to produce well-fitting prostheses using AM. Accuracy consists of two terms: trueness and precision. Trueness is defined by "the closeness of agreement between the average value obtained from a large series of test results and an accepted reference value." While precision is explained by "the closeness of agreement between independent test results obtained under stipulated conditions."[14] For a perfectly accurate implant-supported prosthesis, it should be possible to achieve a passive fit with no marginal gaps or strains repeatedly. The accuracy of different AM techniques will depend on different factors such as printing technology,[11,15,16] material composition,[17] layer thickness,[18] print orientation,[16,19,20] type and number of support structures,[18,19] use of reinforcement bars,[21] and post-processing.[11,17]

It is widely accepted that the accuracy and implant-prosthesis discrepancy of implant-supported dental prostheses highly influence treatment success.[22,23] According to Katsoulis et al[24] the perfect passive fit of the implant-supported prosthesis is achieved when the opposing surfaces of the implants and the framework intaglio are in maximal spatial congruency, without strains in the components after tightening of all screws, provided the implant and framework surfaces are fabricated perfectly plain. A marginal discrepancy ranging from 10 to 150 μm in implant-supported prostheses has been reported as clinically acceptable.[9,24] In cement-retained implant-supported prostheses, some discrepancies might be compensated by the 25 to 50 μm cement space.[10,24] Discrepancies of implant-supported prostheses might evoke biological complications such as perimucositis, periimplantitis, and bone loss.[24,25] However, bone adaptation and decrease in misfit strain were observed when implants were loaded nonpassively inducing mainly mechanical issues.[26] Mechanical issues include screw loosening, fractures of the framework, veneering, or other components.[26,27]

In the in vitro studies, the accuracy of implant-supported cement-retained prostheses can be evaluated by direct microscopy of sectioned or unsectioned samples,[25,28,29] silicone replica technique,[7,12,30] or using computer software[31,32] to do linear measurements of the digitized objects. The implant-prosthesis discrepancy of screw-retained implant-supported prostheses could be measured with the same direct microscopy[11,33] or computer software programs,[9,13,17] as well as strain gauge[4,11,27] analysis. In direct marginal gap microscopy, an irregular finish line of the connections and a 2D view might possess a challenge to accurately measure the misfit. Therefore, improved 3D microcomputed tomography (μCT) techniques were suggested for future studies.[25] Even if the silicone replica technique is considered as a nondestructive, fast, and economic way of determining the internal accuracy of cement-retained prostheses, it is prone to inconsistencies due to manual execution errors, and over- or under-extended marginal fits cannot be detected.[12,30,34] If linear measurements using computer software programs are performed manually then there is a risk of poor landmark identification which compromises the precision of the assessment.[31,32] Strain gauge analysis has its disadvantages too. It is limited to the bonding site and a bias of different bond positions could be introduced into each framework.[11,35] Therefore, studies employing more than one technique of accuracy evaluation are more likely to draw credible conclusions.

Previous systematic reviews have assessed metal AM tooth-supported fixed or removable prostheses accuracy.[10,36–39] However, studies evaluating the accuracy of the AM implant-supported prosthesis have not yet been reviewed systematically. Therefore, a systematic review was conducted to evaluate the accuracy of the metal, ceramic, and polymer screw- or cement-retained implant-supported AM prosthesis.

Materials and methods

This systematic review was performed following PRISMA (Preferred Reporting for Systematic Reviews and Meta-Analyses) guidelines.[40] The following focused question was constructed: What is the accuracy of implant-supported screw- and cement-retained fixed prostheses produced by the AM techniques from metal, ceramic, or polymers?

PICOS (patient, intervention, comparison, outcomes, study design) criteria were used for the inclusion of studies (Table 1). The studies for this systematic review were selected only with a clearly defined accuracy assessment methodology of AM definitive screw- or cement-retained single- or multiple-unit fixed implant-supported restorations made from metal, ceramics, or polymers. Case reports, expert opinions, review articles, and incomplete publications were excluded from this systematic review. Moreover, investigations that included only qualitative evaluation of AM implant-supported restorations, had less than five samples per group, or did not include a control group were also ex-

Table 1 Different factors influencing the accuracy of 3D printed implant-supported prosthesis

Clinical case related	Prosthesis related	3D printing related
1. Span length 2. Number of implants 3. Implant impression method	1. Retention type (screw—or cement—retained) 2. Implant connection type 3. Cement gap 4. Veneering	1. Technology (SLS, DMLS/SLM, EBM) 2. Material (CoCr, Ti, ceramic) 3. Layer thickness 4. Post-processing

Table 2 Inclusion criteria of studies into systematic review based on PICOS guidelines

	Metal 3D printing systematic review
Patients	Partially or completely edentulous dental arch or replica with implants
Intervention	Additive manufacturing of definitive screw- or cement-retained single-unit or multiple-unit fixed implant prosthesis from metal, ceramic, or plastic
Comparison	Accuracy of additively manufactured single-unit or multiple-unit fixed implant prosthesis compared to conventional casting, milling, reference or CAD models
Outcomes	Quantitative estimation of accuracy or fit: linear, angular, volumetric, strain measurements.
Study design	In vivo and in vitro experimental studies

Table 3 Excluded studies and reasons for exclusion

Studies	Reasons for exclusion
Camós-Tena et al[53] 2019; Markarian et al[54] 2018; Alonso-Pérez et al[55] 2017; Fernández et al[56] 2014; Gonzalo et al[57] 2020	Additive manufacturing of the implant abutment or one-piece restoration with internal implant connection
Kim and Lee[8] 2020; Park et al[58] 2019	Additive manufacturing of temporary materials
Taşın et al[59] 2019; Revilla-León et al[60] 2019; Revilla-León et al[43] 2018	Less than 5 samples per group
Altintas and Akin[61] 2020	No reference or control group used
Ogunc and Yildirim Avcu[62] 2021; Yildirim[63] 2020; Castillo-de-Oyagüe et al[64] 2013; Castillo-de-Oyagüe et al[65] 2012; Castillo-de-Oyagüe et al[66] 2012	Evaluation of additional factors (ceramic veneering, mastication simulation, water aging, spark erosion, manual adjusting, etc.) affecting accuracy and dimensional change of AM prosthesis without providing accuracy of 3D printing data before post-processing
Kiliçarslan et al[67] 2014	Dental stone copies of implant abutments used as a reference model for cement-retained implant-supported prosthesis

cluded. Studies evaluating the accuracy of AM of implant abutments with internal connections, AM of interim materials, or ones not registering accuracy data before the use of additional procedures affecting the implant-prosthesis discrepancy (e.g., spark erosion technique) were also excluded (Table 2).

An electronic search was performed in selected databases: MEDLINE/PubMed, Cochrane Central Register of Controlled Trials (CENTRAL), Web of Science, and Google Scholar. Only English language publications were included in this systematic review. The last search was conducted on June 1, 2021. The search strategy was constructed combining free text and MeSH (Medical Subject Headings) terms with Boolean operators (AND or OR): ("Printing, Three-Dimensional"[Mesh] OR "print*" OR "melt*" OR "sinter*" OR "fusion*" OR "additive*") AND "implant*" AND ("abutment*" OR "coping" OR "prosth*" OR "crown*" OR "framework*" OR "denture*" OR "Dental Prosthesis, Implant-Supported"[Mesh]) AND ("Dimensional Measurement Accuracy"[Mesh] OR "accuracy" OR "fit" OR "misfit" OR "adaptation" OR "discrepanc*").

The contents of the following journals were searched additionally using electronic and manual search: *Journal of Prosthetic Dentistry*, *Journal of Engineering in Medicine*, *Journal of Prosthodontics*, *The International Journal of Prosthodontics*, *The Journal of Advanced Prosthodontics*, *Journal of Prosthodontic Research*, *Journal of Oral Rehabilitation, Medical & Biological Engineering & Computing*.

Selected articles were imported into the reference managing software program (Zotero; Center for History and New Media at George Mason University, Fairfax, VA) and two calibrated operators (L.A. and A.G.) screened the titles and abstracts. When additional information was needed, full texts were evaluated. Based on inclusion and exclusion criteria, the final number of the studies were selected for this systematic review. The references of the included full-text articles were additionally reviewed.

Quality Assessment Tool for Diagnostic Accuracy Studies-2 (QUADAS-2) [41] was used to evaluate the methodology of each study. The four risk of bias domains (patient selection, index test, reference standard, and flow and timing) were ranked as low, high, or unknown risk of bias.

Results

An initial electronic search resulted in 537 articles (Fig 1). After the title screening, 44 articles were selected for the abstract review. Eight articles were excluded after the abstract review stage and 33 full-text articles were assessed for eligibility. No additional studies were included after reviewing the references. Finally, 16 in vitro studies were included in this systematic review. Excluded publications and reasons for the rejection are listed in Table 3. Four studies evaluated complete-arch,[9,11,13,17] seven—multiple-unit,[4,27,30–33,42] and five—single-unit implant-supported prostheses.[7,12,25,28,29]

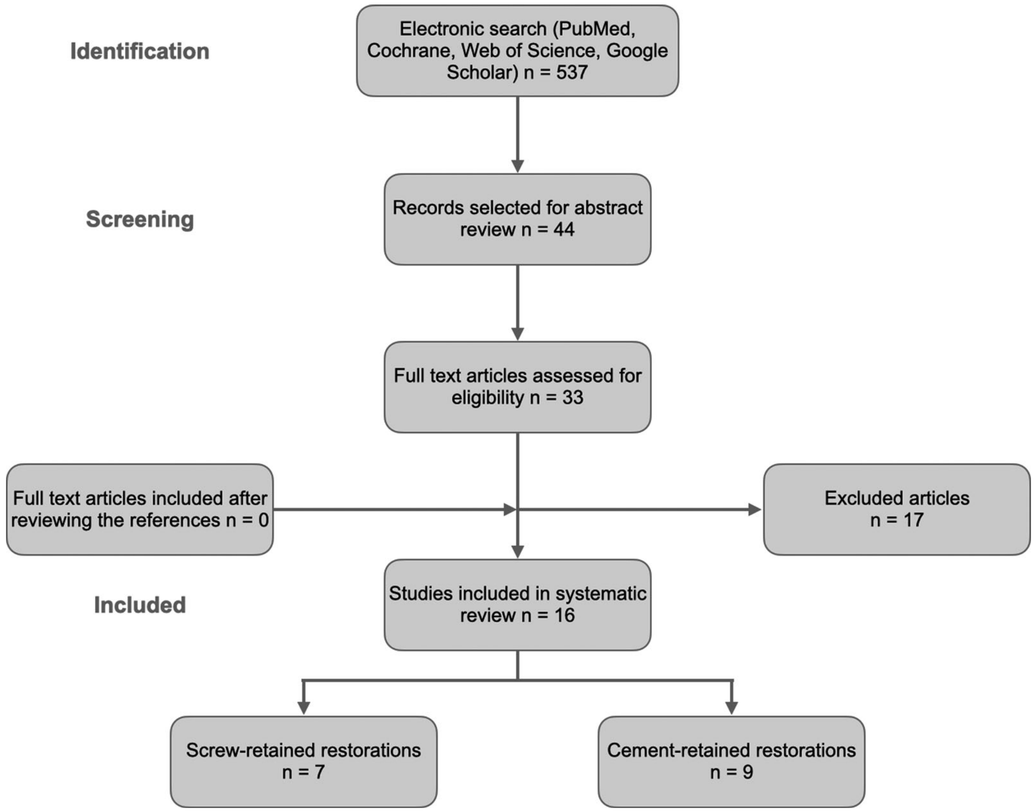

Figure 1 Scheme of study selection for the systematic review.

Seven of included studies investigated screw-retained implant-supported restorations[4,9,11,13,17,27,33] and nine cement-retained prostheses.[7,12,24,28–32,42] The majority of the studies evaluated additive manufacturing of CoCr (n = 12),[4,9,12,25,27–33,42] three—titanium alloys,[11,13,17] and one—zirconia[7] materials. The details of selected studies have been extracted into Tables 4–6.

Study characteristics

Sample size in the included studies varied from five[11] to twelve[42] samples per group. Seven studies investigated the restorations in the mandible,[4,9,13,29,31,32,42] six in the maxilla,[7,11,17,27,28,30] and in three papers[12,25,33] the jaw was not mentioned, but the specimens were prepared on the custom made model. Multiple-unit implant-supported fixed dental prostheses (FDPs) were supported by two or three dental implants, while complete-arch restorations were made on four or six implants. The majority of publications used milled restorations as a control group to evaluate the accuracy of additively manufactured prostheses (n = 7).[7,11,13,17,31,33,43] Both cast and milled restorations were compared with AM ones in six studies,[12,25,28–30,32] and three studies[4,27,42] used only cast implant-supported restorations as a control group.

Additive manufacturing

Several types of AM techniques were documented in the selected publications. SLM was documented in nine studies,[4,9,11,13,17,25,30–32] DMLS in five,[12,27–29,42] EBM in one study[11] and stereolithography in one study.[7] AM technique was not specified in one study.[33] Seven studies[4,11,17,25,29,30,42] have documented the layer thickness of AM material, which varied from 20 to 50 µm. In nine studies[7,9,12,13,27,28,31–33] the details were not mentioned. Post-processing protocol of the tested restorations was mentioned in five studies,[4,12,28–30] which included sandblasting with aluminum-oxide particles or heat treatment. Barbin et al[11] also investigated the impact of spark erosion on the implant-prosthesis discrepancy improvement of the frameworks.

Assessment methodology

Various types of methods were documented for accuracy assessment of AM restorations such as strain (n = 3)[4,11,27] and photoelastic stress analysis (n = 2),[4,11] silicone replica technique (n = 6),[7,12,29–32] and linear measurements of marginal discrepancies using microscopy (n = 5)[11,25,28,33,42] or coordinate measuring machine (n = 2).[9,17] Additionally, the digital accuracy assessment method was documented in three studies as a technique for accuracy evaluation. Prosthetic screw-loosening torque analysis and chewing simulation were also described as additional accuracy tests in one study.[11]

Outcomes assessed/main findings

Studies that used strain and photoelastic stress analysis for accuracy evaluation presented controversial conclusions.

Table 4 Details of selected studies that evaluated AM cement-retained prostheses

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Revilla-León et al[7] 2020	Zirconia (3D Mix ZrO2, 3D Ceram Co) -	SLA (CERAMAKER 900, 3DCeram Co)	None	Mill ZrO2 (CARES zirconium-dioxide crown; Institut Straumann AG)	None	1-unit	Cement, NA	1	Bone level RC (Straumann) with custom made ZrO abutment	10	Lab scanning (DentalWings 7 series)	Linear	Silicone replica technique	The CNC milling group had the least marginal and internal discrepancies compared with the two AM groups: splinted and anatomic. Anatomic AM specimens had clinically unacceptable marginal and internal crown discrepancies.
Aktas et al[25] 2021	Co-Cr (EOS Cobalt Chrome SP2; EOS GmbH) 20 µm	SLM (EOSINT M270, EOS)	Sandblasting	Mill Co-Cr (NA) (Magnum Lucens, Giacomo and C.S.N.C.), Cast Co-Cr (INF 2010, Mikrotek Dental) (Wirobond C, Bego Dental)	Sandblasting	1-unit	Cement, 40 µm	1	Custom made CAD/CAM implant abutment	10	Lab scanning (DentalWings 7 series)	Linear	Marginal gap microscopy	The SLM method resulted in the lowest mean marginal discrepancy among the specimens.
Yildirim and Paken[12] 2019	Co-Cr (Eos Cobalt Chrome SP2; Eos Optical Systems) -	DMLS (Eos Optical Systems, Krailling, Germany)	None	Cast Co-Cr (Fornax T; Bego) (Wirobond C; Bego), Mill Co-Cr (Starbond, Scheftner, Germany) (NA)	Cast Co-Cr Sandblasting; hand finishing, polishing Mill Co-Cr None	1-unit	Cement, 25 µm	1	Titanium abutments (Megagen) on implant replicas (Megagen, internal)	12	Lab scanning Milling (D800, 3Shape) DMLS (3D Scanner; Eos Optical Systems)	Linear	Silicone replica technique	The milling group showed significantly lower marginal fit than the cast and AM groups. In the CAD/CAM group, marginal gap values were slightly higher than the clinically acceptable values. The marginal fit of the cast group was not significantly different from the AM group. All fabrication methods demonstrated similar intermarginal and occlusal fit.

(*Continued*)

Table 4 (Continued)

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Zhou[31] et al 2019	Co-Cr (NA) -	SLM (NA)	NA	Mill (NA) (Co-Cr)	NA	4-unit	Cement, NA	2	Abutment analogs (048.5416; Straumann, internal)	10	Lab scanning (D810, 3Shape)	Linear	Digital superimposition; Silicone replica technique	The analysis of distances between the dots and marginal gap width showed significantly higher accuracy of milled prostheses than AM.
Akçin et al[30] 2018	Co-Cr (EOS Cobalt Chrome SP2; EOS GmbH) 30 µm	SLM (EOS Cobalt-Chrome SP2; EOS GmbH)	Sandblasting	Mill Co-Cr (DC40; Yena Machinery) (Magnum Lucens, Giacomo and C.S.N.C.); Cast Co-Cr (NA) (Wirobond C, Bego Dental)	Sandblasting	3-unit, 4-unit, 5-unit	Cement, 50 µm	3-unit and 4-unit on 2 implants, 5-unit on 3 implants	Titanium abutments and implants (Astra Tech Implant System, Dentsply Sirona, internal)	10	1-stage abutment-level analog impressions were made (N = 1). Stone models pured and lab scanning performed (NA)	Linear	Silicone replica technique	The mean marginal discrepancy of 3-unit frameworks showed no statistically significant differences in the cast and AM techniques. However, the frameworks manufactured by milling had the highest marginal discrepancy values. No significant differences were found among the manufacturing techniques of 4-unit frameworks. For 5-unit frameworks, CAD-CAM milling techniques had the widest mean marginal discrepancy values, while the cast group was the most accurate.

(Continued)

Table 4 (Continued)

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Görüş and Üner[28] 2018	Co-Cr (SINTTECH, Clermont-Ferrand) -	DMLS (EOSINT M 280, EOS GmbH Electro Optical Systems)	NA	Cast Co-Cr (Mikrotek) (Microlite Heat, Schütz Dental Group), Mill Co-Cr (Fedi 18, Mariotti & C. Attrezzatura Dentale) (NA, Whitepeaks Dental Systems GmbH & Co.) Noritake Alliance system (NA) (Noritake Alliance Y-TZP blocks, Noritake Dental Supply Co. Ltd.)	Cast Co-Cr Sandblasting Mill Co-Cr NA Noritake Alliance system Ultrasound cleaning with distilled water	1-unit	Cement, 10 µm	1	Tissue level implant abutments (NTA, Shorter)	10	Milling Co-Cr lab scanning (NA, Dental Wings, Inc), DMLS lab scanning (Indian-Els Scanner, Indian-Els DentaCAD Systeme), Noritake Alliance Y-TZP (*Optical Scanner S600)*	Linear	Marginal gap microscopy	The smallest value of the marginal gaps was found in the Noritake system, followed by AM and cast groups. The largest value was found in the milling. However, all methods produced clinically acceptable marginal fit.

(*Continued*)

Table 4 (Continued)

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Zhou et al[32] 2017	Co-Cr (NA) -	SLM (Bego EOS-M280)	NA	Mill Co-Cr (NA) (Original Multi and Changer 20 RK),	NA	2-unit, 3-unit, 4-unit	Cement, NA	2	Solid abutment analogs (Straumann 048.5416)	6	Lab scanning (D810, 3Shape)	Linear	6 distances per framework were measured digitally between the dots (Ø 0,2 mm)	SLM group was more accurate than cast, but inferior to milled samples. The longer is the span legth, the bigger deviations occur despite the manufacturing technique. Marginal gap deviations were lower than 80 µm in all groups.
				Cast Co-Cr (NA) (Mo)	NA							Linear	Silicone replica technique	
Kim et al[29] 2017	Co-Cr (EOS Cobalt ChRome SP2, Biomain AB) 30 µm	DMLS (EOS EOSINT M270, EOS GmbH—Electro-Optical Systems)	Sandblasting; Heat treatment	Cast Co-Cr (Seki Dental Co.) (JEWOOS02, JEWOO M-Tech) Mill Co-Cr (DNM-500, SMT Solution Co.) (Starbond CoS, S&S Scheftner GmbH)	Cast Co-Cr Sandblasting Mill Co-Cr None	1-unit	Cement, 30 µm	1	Transfer type abutment TS system (Osstem, NA)	12	Lab scanning (D800, 3Shape)	Linear and weight	Silicone replica technique (by weighing silicone and marginal gap microscopy); Cemented prosthesis sectioning and microscopy	Additively manufactured prosthesis had the worst accuracy when compared to cast and milling groups. However, all prostheses had clinically accpetable accuracy.
Castillo-de-Oyagüe et al[42] 2012	Co-Cr (ST2724G, Sint-Tech) 20 µm	DMLS (PM 100 Dental; Phenix Systems)	NA	Cast Co-Cr (*) (Gemium-cn, American GMG Inc.), Cast Ni-Cr-Ti (*) (Tilite, Talladium Inc.), Cast Pd-Au (*) (Jensen GmbH) * MIE-200 C/R, Ordenta, Arganda del Rey	Sandblasting	3-unit	Cement, NA	1	Ti abutments (Implant Microdent System)	12	Lab scanning (Cercon Eye, Dentsply)	Linear	Marginal gap microscopy	For each of the cements tested, AM samples exhibited the best marginal adaptation when compared to other groups.

Table 5 Details of selected studies that evaluated AM screw-retained prostheses with additional CNC milling

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Del Monte et al[33] 2021	Co-Cr (NA) -	NA (Renishaw, Wotton -under-Edge, UK)	CNC milling (NA)	Mill Co-Cr (NA) (NA)	NA	3-unit	Screw	2	Regular Neck Straumann implant analog (Straumann, internal)	10	Lab scanning (Cares scanner, Straumann)	Linear	Marginal gap microscopy	AM prostheses presented a marginal fit comparable to milled.
Revilla-León et al[9] 2020	Co-Cr (SP2 Co-Cr metal powder; EOS) -	SLM (EOS M100; EOS)	CNC milling (DMG 10 Ultrasonic; DMG Mori)	Mill Co-Cr (Atlantis Bridge Co-Cr; Dentsply Sirona) (NA)	NA	full-arch	Screw	6	Implant abutment replicas (Multi-unit Abutment RP Replicas; Nobel Biocare Services AG, multi units)	10	Lab scanning (D1000, 3Shape)	Linear and angular	CMM scanning and superimposition of center points (of reference model and frameworks)	No significant differences were found between the CNC and AM groups in the implant abutment-prosthesis measurements
Ciocca et al[13] 2019	Ti–6Al–4V (NA) -	SLM (EOSINT M270, Electro-Optical Systems)	CNC milling (CORiTEC 350i, Imes-Icore GmbH)	Mill Co-Cr (PICOMAX 60HSC, Felhman) (ECHO)	NA	full-arch	Screw	6	Premium (Sweden & Martina, internal)	9	IOS (True Definition Scanner; 3M ESPE), OCMM (SmartScope Flash CNC 300; Optical Gaging Products)	Linear	Error for each framework was described as variation in the spatial position of the 6 PFI center points.	Both hybrids were more accurate, with statistical significance, than the milling technology. Trueness levels observed in all groups were well within the clinically acceptable limit. No significant precision differences among the groups were recorded.
		SLM (Concept Laser 41 TI, Concept Laser)	CNC milling (Mikron Mill-S 400U, GF Machining Solutions)									Linear	CAD design superimposed with an STL of a fabricated prosthesis. Position error between paired platform positions	

(*Continued*)

Table 5 (Continued)

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Svanborg et al[17] 2018	Ti–6Al–4V (extra low interstitial (ELI) powder, Renishaw), Co-Cr (Renishaw DG1, Renishaw) 40-µm	SLM (Renishaw AM 250)	Heat treatment; CNC milling (Willemin Macodel)	Mill Ti–6Al–4V (NA) (NA) Mill Co-Cr (NA) (NA)	Mill Ti–6Al–4V Mill Co-Cr	full-arch	Screw	6	Balance base abutment narrow 5.5 (Ankylos, Dentsply Sirona Implants, internal)	10	Lab scanning (NA)	Linear and angular	After scanning with CMM, framework center points were placed in a virtual "best fit" position onto the abutment replica center point positions. Center point coordinates, before and after ceramic veneering, were compared. Also, the angulations of each center point were reported in three dimensions (x, y, and z axes) and 3D.	Discrepancies of all groups (CNC and AM) fit well within the range of 20 µm.

Table 6 Details of selected studies that evaluated AM screw-retained prostheses without additional CNC milling

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Arroyo-Cruz et al[27] 2021	Co-Cr (Keramit NP-S alloy; Nobil-Metal S.p.A.) -	DMLS (mysint100; Sisma S.p.A)	NA	Cast Co-Cr (Induction casting machine Mie200; Ordenta Sudenta) (∗), Mill Co-Cr (Mikron HSM400 ULP; GF Machining Solutions Ltd) (∗), ∗ ERGILOY 9.9229 HW PREMIUM; ZAPP Precision Metals GmbH	NA	3-unit	Screw	2	Mgosseous (Ticare MG-Osseous, external)	10	Lab scanning (S600 Arti; Zirkonzahn)	Strain	Strain gauge	Milled structures displayed a better accuracy, followed by sintered structures. Cast structures had the worst accuracy with an increased risk of fracture.
Presotto et al[4] 2019	Co-Cr (remanium Star CL, Powder 10 to 40 mm; Concept Laser GmbH) 25 µm	SLM (Mlab Cusing 200R; Concept Laser GmbH)	Heat treatment; Sandblasting	Cast Co-Cr (NA) (StarLoy C; DeguDent GmbH) Mill Co-Cr (Ceramill Motion 2; Amann Girrbach) (Ceramill Sintron blocks; Amann Girrbach)	Cast Co-Cr Sandblasting; Hand finishing, polishing Mill Co-Cr Sandblasting	3-unit	Screw	2	Mini-abutment cylinder (SIN-Sistema de Implante, Multiunit abutments)	10	Lab scanning (Ceramill Map 300 Scanner; Amann Girrbach)	Strain	Photoelastic and strain gauge	FPDs frameworks made by SLM technology showed lower levels of marginal fit, stress, and strain.

(*Continued*)

Table 6 (Continued)

Author, year	AM material; (product); layer thickness	AM method (machine)	Post-processing of the AM specimens (equipment)	Control group. Manufacturing technique (machine) (material)	Post-processing of control groups	Prosthesis	Retention, cement space	Implant number	Implant system (abutment, implant model, connection, manufacturer)	N per group	Impression (method or machine)	Measurement	Assessment method	Test Results
Barbin et al.[11] 2020	Ti–6Al–4V SLM (CL 41TI ELI, Concept Laser GmbH) 25 µm EBM (Arcam Titanium Ti6Al4V, Arcam EBM System, Ge Additive Company) 50 µm	SLM (MLab Cusing 200R, Concept laser, GmbH), EBM (Arcam Q10Plus, Arcam EBM, Ge Additive Company)	NA	Mill Ti–6Al–4V (CNC D15W, Yenadent) (Starbond Ti5 Disc, Scheftner)	NA	full-arch	Screw	4	Easy Grip Porous (Conexao Prosthesis System, multi units)	5	Lab scanning (Ceramill map 400+, Amann Girrbach)	Torque; Strain; Linear	Screw-loosening torque analysis; Strain-gauge and photoelastic analysis; Marginal gap microscopy	1. Milled frameworks presented lower marginal gap discrepancies than AM groups; 2. Milled frameworks presented higher screw-loosening values than AM groups; 3. Milled frameworks presented lower mean stress values than did AM groups, regardless of evaluation time.

Table 7 Criteria for low-risk domain ranking

Patient Selection	• Reference model does not influence the measurement results significantly
	• Statistical calculations are made to determine the required sample size
Index Test	• Same impression was used to produce the test and control group samples
	• Layer thickness of the additive manufacturing is provided
	• Cement gap is provided for the cement-retained restorations
	• The test group observer is blinded or independent
	• Detailed information provided about the measurements on the test group samples
	• Detailed information provided about the materials and machines used to produce the samples of the test group
Reference Standard	• Same impression was used to produce the test and control group samples
	• Cement gap is provided for the cement-retained restorations
	• The control group observer is blinded or independent
	• Detailed information provided about the measurements on the control group samples
	• Detailed information provided about the materials and machines used to produce the samples of the test group
Flow and Timing	• The execution of the study does not influence the test results significantly

Arroyo-Crus et al[27] reported that milled restorations demonstrated better accuracy than sintered ones, while others documented that interaction of manufacturing technique and evaluation time was not significant.[11] Moreover, the study of Pressoto et al[4] presented that AM implant-supported FDPs showed the lowest stress and strain levels compared to milled or cast ones.

Silicone replica accuracy assessment method revealed that in most cases milled prosthesis demonstrated better accuracy than AM.[7,31,32] Yildirim et al[12] reported that AM, cast, and milled prosthesis demonstrated similar intermarginal and occlusal fit, while Akcin et al[30] demonstrated that AM frameworks showed the lowest marginal discrepancies for shorter span length restorations, while cast 5-unit implant-supported prostheses were more accurate than milled or AM ones. In the other study, AM implant-supported restorations were less accurate compared to cast and milled prosthesis, but still, they were qualified as clinically acceptable, because marginal discrepancies were lower than 150 μm.[29]

Several types of microscopies were also used for accuracy evaluation. The majority of studies concluded that AM prostheses were comparable to milled or cast ones or their differences were clinically not significant.[9,17,28,33,42] However, another study documented the smallest marginal gap of SLM manufactured prosthesis compared to milled and cast prosthesis despite the configuration of the anti-rotational feature of the implant abutment.[25]

Two studies used digital accuracy assessment tools and revealed that AM implant-supported restorations were less accurate than milled ones, but described marginal discrepancies as clinically acceptable.[31,32] The other study documented the results of the superimposition method where hybrid AM and milled prosthesis demonstrated better accuracy than milled restorations.[13]

Overall, only two[4,13] studies from six which tested screw-retained implant-supported restorations claimed that additively manufactured specimens were more accurate than milled or cast ones. AM cement-retained implant-supported restorations also were documented as more accurate than control groups only in two publications.[30,42] The most common finding was that AM restorations demonstrate better accuracy than cast, but less or similar accuracy to milled ones. From the publications which used DMLS technology for AM, two have concluded that AM showed poorer results than milling,[27,29] two stated similar accuracy with milling,[12,28] and one claimed that AM demonstrated the highest accuracy values compared to other manufacturing methods.[42] SLM technique was discussed in nine selected studies, most of them concluded that AM demonstrated lower accuracy values than milling,[9,11,31,32] three claimed that the accuracy results are similar,[17,25,30] and two publications concluded that AM restorations were more accurate than milled ones.[4,13] However, the accuracy differences among AM, milled, or cast restorations were claimed to be clinically insignificant.

Risk of bias assessment

The criteria for domain ranking are presented in Table 7. High risk was considered in a domain when at least one criterion was not fulfilled. Only four studies mentioned the statistical method of sample size calculation.[11,12,25,30] Only two studies fulfilled all index test requirements. [4,29] Two studies used different methods to obtain a digital impression for prosthesis fabrication[12,28] and the study by Svanborg et al[17] lacked information about the impression. Seven out of sixteen studies [4,11,17,25,29,30,42] documented the layer thickness of the AM methods selected. The cement space value was not mentioned in three studies.[7,32,42] In the majority of the studies ($n = 10$) observer was not blinded or independent.[7,9,11–13,25,28,30,32,33] Lack of detailed information about either materials or machines used in the study was also observed in several studies.[9,13,28,31–33] The quality of reference standard is unknown in the study of Svanborg et al[17] Finally, two studies were considered as having a high risk of bias in flow and timing domain: samples of Del Monte et al[33] study were manufactured in different countries while the accuracy of Svanborg et al[17] test samples was measured on the same stone reference models from the previously conducted research. Each study and the corresponding domain quality evaluation is presented in Table 8. A bar chart represents the proportional distribution of the rankings (Fig 2).

Discussion

Computer-aided design and computer-aided manufacturing (CAD-CAM) technologies have greatly improved the process of prosthesis manufacturing, but still have some limitations.

Table 8 Risk of bias evaluation according to QUADAS-2 domains

Study	Risk of bias			
	Patient selection	Index test	Reference standard	Flow and timing
Arroyo-Cruz et al[27] 2021	−	−	+	+
Del Monte et al[33] 2021	−	−	−	−
Aktas et al[25] 2021	+	−	−	+
Barbin et al[11] 2020	+	−	−	+
Revilla-León et al[9] 2020	−	−	−	+
Revilla-León et al[7] 2020	−	−	−	+
Presotto et al[4] 2019	−	+	+	+
Yildirim and Paken[12] 2019	+	−	−	+
Zhou et al[31] 2019	−	−	−	+
Ciocca et al[13] 2019	−	−	−	+
Akçin et al[30] 2018	+	−	−	+
Görüş and Üner[28] 2018	−	−	−	+
Svanborg et al[17] 2018	−	−	?	−
Zhou et al[32] 2017	−	−	−	+
Kim et al[29] 2017	−	+	+	+
Castillo-de-Oyagüe et al[42] 2012	−	−	−	+

+ Low Risk; − High Risk; ? Unclear Risk

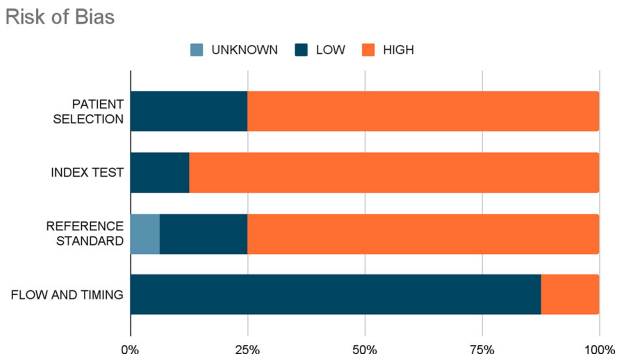

Figure 2 Proportional distribution of bias evaluation rankings.

An AM technique has been invented as an alternative to the milling process which should reduce material waste, improve the density of the restoration, and serve as an option to produce fine details of the prosthesis not dependent on the amount or size of the milling burs' system.[34,44] However, AM is susceptible to specific errors, depending on different AM techniques or equipment.[2]

A distinctive feature of AM metal implant-supported prosthesis is the surface roughness, which depends on the AM technique employed.[11] To improve accuracy and implant-prosthesis discrepancy, connections can be subsequently milled with a CNC machine.[9,13,33] Out of seven selected studies that evaluated AM metal screw-retained prostheses, three[4,11,27] did not perform CNC milling and stated inferior accuracy of the AM samples when compared to milled ones. The other four studies[9,13,17,33] that performed CNC milling of AM prostheses stated the opposite—AM prostheses are of comparable or even higher accuracy than their milled counterparts.

No information was mentioned in any of the selected papers about manual adjustments of AM frameworks. Two publications stated that no final adjustments were done at the marginal or internal area of the restorations after printing.[7,12] In the other five articles, heat treatment[4,17,28,29] and sandblasting[4,11,29,30] were mentioned as final processing methods, while four noted machined milling as a final step of manufacturing of AM restorations.[9,13,17,33] Clinically, manual internal refinement of the coping by a dental technician can significantly improve the marginal accuracy. [45]

Several reviews have been published about additively manufactured dental restorations.[2,5,10,46,47] The accuracy of the tooth- and implant-supported restorations has only been documented in general, but this study serves the relevant systematized data about the accuracy of AM fixed implant-supported prostheses exceptionally. Because of the manufacturing and construction differences between tooth- and implant-supported restorations such as scanning of the preparation margin or capturing the virtual position of the implant with scan body, tolerance of marginal gap discrepancies or passivity, fixation type, and the more specific data about implant-supported restorations was required.

Marginal gap evaluation of implant-supported restorations was conducted in various methods, such as microscopy,[11,25,28,33,42] silicone replica technique,[7,12,29–32] and measuring with the coordinate measuring machine.[9] According to well-documented results, marginal gap values of conventionally milled implant-supported restorations' in laboratory studies vary from 1 to 27 µm.[48] In this study higher values of the additively manufactured prostheses have been detected which vary from 41[25] to 146[7] µm of single-unit, from 23[33] to 61[30] µm of multiple-unit, and from 54[9] to more than 200[11] µm of a complete-arch prosthesis. AM restorations demonstrated inferior accuracy results to milled restorations, but mostly all of them were deemed clinically acceptable, considering the range of the limit from 10[49] to 150[50] μm. Moreover, according to results, the manufacturing technology has no impact on the accuracy of different span length prostheses. However, all included studies were performed in laboratory conditions, so the results have to be taken with caution.

Stress analysis was conducted for three-unit[4,27] and complete-arch[11] screw-retained implant-supported prostheses. Both short-span FDPs and complete-arch implant-supported restorations made by milling from metal blocks were found to be more accurate than AM or cast ones.[11,27] However, Pressoto et al[4] claimed that AM 3-unit FDPs on implants had better accuracy than milled or cast ones. Due to the limited number of studies that assessed the stress analysis of the frameworks, it cannot be concluded that manufacturing technology could have a negative impact on the accuracy of the different span-length prostheses.

Only one included study evaluated the prosthetic screw stability of differently manufactured prostheses after 24 hours of tightening and also performed chewing simulation.[11] Milled complete-arch restorations demonstrated the higher screw-loosening strength of all tested specimens. Such results were explained by the very smooth milled surface of the prosthesis connection, which increases friction forces and leads to higher screw stability. The rougher surface and less intimate contact between prostheses and abutments are obtained after AM, and the prosthetic screw loses its stability more easily during the function. This problem is solved using hybrid AM combined with milling technique when the connection part of the prosthesis is additionally milled to create a surface as smooth as possible and ensure complete congruence of the framework and the abutment.[13]

Several studies used a digital method for the accuracy assessment of the prosthesis.[13,31,32] Tested frameworks were of different span lengths: from two-unit[31,32] to complete-arch frameworks.[13] Analysis of shorter span-length prosthesis revealed that AM restorations were more accurate than cast but less than milled restorations.[31,32] However, the measurement method used in the study has some limitations. Dots (0.2 mm in size) were placed on each framework CAD model as the reference marks. After prosthesis manufacturing, they were scanned again and the reference dots were used to perform selected measurements. The complexity of the method could cause higher standard deviations and compromise the evaluation of the precision parameter. Moreover, because of the big number of measurements, their values were averaged for a more favorable calculation. Therefore, the presented results should be taken with caution. In the study of Ciocca et al,[13] additively fabricated prostheses were scanned with an industrial optomechanical coordinate measuring machine. After the data processing, the trueness and precision of manufacturing technology were evaluated comparing the scans of the tested prostheses with their CAD models. The analysis has revealed that additively manufactured prostheses demonstrated better trueness and precision than milled ones.

An alternative digital method to assess the accuracy of the screw-retained multiple-unit implant-supported prosthesis was presented by Svanborg et al[17] and Revilla-León et al.[9] A coordinate measuring machine was employed to scan the AM specimens and the reference model. Then center points of connecting platforms were automatically calculated and put into best fit using the metrology software. The linear and angular deviations between the corresponding center points of the framework and reference model were recorded and compared. Theoretically, in this measurement method center points of the prosthesis connections can be placed more apically than the center points of the implant or abutment. Such overlapping is physically impossible. Therefore, inaccuracies might be more severe clinically than calculated by the software. These errors are avoided when the final prosthesis is superimposed on the original CAD file.[13]

Accuracy evaluation was a focus in this review. However, the durability of veneering has to be considered when choosing an AM framework for implant-supported prosthesis. According to Abduo et al,[51] AM metal frameworks with complex 3D network design are more resistant to acrylic veneer flexural cracks and result in less severe chippings than with milled prostheses. AM metal prosthesis, when compared to the milled ones, might be more susceptible to deformations after ceramic veneering but still maintain a clinically acceptable fit.[9,17] It was reported, that air bubbles and cracks formed more often in the ceramic veneering of AM Ti frameworks than in milled CoCr, Ti, and AM CoCr groups.[17] Biocompatibility is mainly material dependent and Ti, CoCr, and zirconia are considered safe for producing AM dental prosthesis.[3] Despite inclusion criteria covering all materials suitable for permanent implant-supported prosthesis, only one study[7] evaluated zirconia AM prostheses. Production of ceramic AM prostheses is more challenging because of high esthetic, mechanical requirements, and additional procedures of debinding and sintering.[3] Further studies about ceramic implant-supported AM prostheses are needed to evaluate optical and mechanical properties.

The accuracy of additively manufactured implant-supported prostheses is highly dependent on the materials, machines, and measurement methods employed.[5,10,52] In the current review, selected studies presented some degree of bias and heterogeneity. The inclusion of more detailed information about the devices, materials used in the study, postprocessing protocol of the AM restorations, and statistical calculation-based sample sizes should improve the quality of future studies and could ensure more reliable conclusions. The reference model should also be stable over time and provide similar measurement conditions for all samples. It is advisable to perform blinded or independent accuracy observations with repeatable measurement techniques because imprecise manual landmark identification could affect the results.[32] Since the accuracy of AM implant-supported prosthesis can be affected by many factors and methodology aspects specific for each study, all laboratory experiment results have to be taken with caution. Therefore, further randomized clinical trials are needed to evaluate the accuracy of the newest technologies. AM methodology demonstrates promising results in the accuracy of implant-supported restoration manufacturing, so further goals should be focused on prosthesis density, post processing methods improvement, and availability of more materials.

Conclusions

Within the limitations of this systematic review, further conclusions can be drawn. Additively manufactured implant-supported fixed prostheses demonstrate similar accuracy compared to conventional and subtractive techniques in vitro. Detected inaccuracies of additively manufactured implant-supported restorations do not exceed currently acceptable clinically significant limits. 3D printing equipment and technique-related factors can define the rationale to additionally apply the milling for further improvement of the fit. Technological and manual post-processing can significantly influence the implant-prosthesis discrepancy of implant-supported prostheses fabricated by AM technology with or without additional milling. More well-controlled studies are needed to investigate the accuracy and clinical applications of AM prostheses using ceramics and polymers.

Conflict of interest statement

Authors declare no conflicts of interest.

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