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DOI: https://doi.org/10.1111/clr.14085

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Journal Article
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Originally published at:
Ioannidis, Alexis; Pala, Kevser; Strauss, Franz J; Hjerppe, Jenni; Jung, Ronald E; Joda, Tim (2023). Additively and subtractively manufactured implant-supported fixed dental prostheses: A systematic review. Clinical Oral Implants Research, 34 Suppl:50-63.
DOI: https://doi.org/10.1111/clr.14085

Check for updates

Received: 6 February 2023 | Revised: 24 April 2023 | Accepted: 26 April 2023

DOI: 10.1111/clr.14085

REVIEW ARTICLE

CLINICAL ORAL IMPLANTS RESEARCH WILEY

# Additively and subtractively manufactured implant-supported fixed dental prostheses: A systematic review

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International Team for Implantology

## Abstract

**Aim:** To compare and report on the performance of implant-supported fixed dental prostheses (iFDPs) fabricated using additive (AM) or subtractive (SM) manufacturing.

**Methods:** An electronic search was conducted (Medline, Embase, Cochrane Central, Epistemonikos, clinical trials registries) with a focused PICO question: In partially edentulous patients with missing single (or multiple) teeth undergoing dental implant therapy (P), do AM iFDPs (I) compared to SM iFDPs (C) result in improved clinical performance (O)? Included were studies comparing AM to SM iFDPs (randomized clinical trials, prospective/retrospective clinical studies, case series, in vitro studies).

**Results:** Of 2′184 citations, no clinical study met the inclusion criteria, whereas six in vitro studies proved to be eligible. Due to the lack of clinical studies and considerable heterogeneity across the studies, no meta-analysis could be performed. AM iFDPs were made of zirconia and polymers. For SM iFDPs, zirconia, lithium disilicate, resin-modified ceramics and different types of polymer-based materials were used. Performance was evaluated by assessing marginal and internal discrepancies and mechanical properties (fracture loads, bending moments). Three of the included studies examined the marginal and internal discrepancies of interim or definitive iFDPs, while four examined mechanical properties. Based on marginal and internal discrepancies as well as the mechanical properties of AM and SM iFDPs, the studies revealed inconclusive results.

**Conclusion:** Despite the development of AM and the comprehensive search, there is very limited data available on the performance of AM iFDPs and their comparison to SM techniques. Therefore, the clinical performance of iFDPs by AM remains to be elucidated.

KEYWORDS
additive manufacturing, CAD-CAM, Computer-Aided Design, Computer-Aided Manufacturing, dental implants, Dental Prosthesis, Implant-Supported, single tooth, 3 Dimensional Printing, 3 D Printing, Three-Dimensional Printing

## 1 | INTRODUCTION

With the advent of digital technologies in implant dentistry, conventional surgical and prosthetic approaches have been increasingly replaced or complemented by digital workflows (Jung et al., 2009; Muhlemann et al., 2018; Schneider et al., 2021). These technologies pursue toward a common goal: the optimization of current treatment options in implant dentistry (Al-Dwairi et al., 2019; Joda

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et al., 2017, 2021; Kunavisarut et al., 2022; Muhlemann et al., 2022; Pan et al., 2019).

Conventional prosthetic workflows have shown predictable long-term results, but involve more manual effort and treatment time, and are more technique-sensitive (Joda & Bragger, 2016). To overcome these limitations, digital workflows, using computer-aided design (CAD) as well as computer-aided manufacturing (CAM) for the fabrication of the prostheses, have been introduced (Mormann et al., 1990; Muhlemann et al., 2018). The CAM process for the different restorative materials relies on two methods: (1) SM: subtractive manufacturing or (2) AM: additive manufacturing (Pyo et al., 2020).

Subtractive manufacturing methods involve the milling of a manufacturing material to obtain an interim or final restoration. SM has become a well-established technology in implant dentistry producing accurate implant-supported fixed dental prostheses (iFDPs; De Angelis et al., 2020; Gintaute et al., 2021; Muhlemann et al., 2020). Nevertheless, there are some limitations such as the large amounts of waste due to material residues generated during the grinding of the material block. In addition, the SM technology is limited to some extent by the complexity of the structures, as the number of milling axes and number and shape of the milling instruments limit the possible design and affect the reproduction of an object (Methani et al., 2020; Revilla-Leon, Besne-Torre, et al., 2019). Furthermore, during the milling processes of ceramics, the material's high strength can lead to an increased wear of the milling instruments (Methani et al., 2020).

Additive manufacturing, commonly referred to as 3D printing, describes the process of successive adding and joining materials layer by layer to build a digitally designed three-dimensional object by means of a 3D printer (Jockusch & Ozcan, 2020). The AM technology allows the inclusion of different material properties or colors in the same workpiece (Methani et al., 2020; Stansbury & Idacavage, 2016). Moreover, AM may bring the advantage of reduced material waste and enables the recycling of unused material (Galante et al., 2019). There are different technologies and materials used for AM. The quality of a product, as well as the production time and costs, can be affected by various factors such as the technology used, its resolution, processing parameters (e.g. the energy source, layer thickness, or building orientation), material composition, and required post-processing treatments. (Alharbi et al., 2016; Osman et al., 2017; Tian et al., 2021).

In in vitro studies, both AM and SM methods have shown similar precision for the fabrication of tooth-supported fixed dental prostheses (Ioannidis et al., 2021; Son et al., 2021; Wang et al., 2019). A previous systematic review comparing SM to AM for iFDPs reported inconclusive results, in part due to a limited number of studies applying AM (Muhlemann et al., 2021). Due to the significant and ongoing interest in additive manufacturing, it is crucial to analyze and summarize the latest state of evidence in order to arrive at more definitive conclusions about this fabrication method. The aim of the present systematic review was, therefore, to compare and report on the performance of iFDPs fabricated using AM or SM techniques.

## 2 | MATERIALS AND METHODS

### 2.1 | Protocol development registration and reporting format

A detailed protocol was developed and followed according to the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) statement (Page et al., 2021) and the 2021 Cochrane Handbook (Higgins et al., 2021). The protocol was registered in PROSPERO with the identification number CRD42021293470.

### 2.2 | Eligibility criteria

According to the PICO-framework, a focused question was utilized to facilitate the inclusion and exclusion of studies.

#### 2.2.1 | Focused question

In partially edentulous patients with missing single (or multiple) teeth undergoing dental implant therapy (P), do AM iFDPs (I) compared to SM iFDPs (C) result in an improved clinical performance (O)?

Population (P): Partially edentulous patients with missing single (or multiple) teeth undergoing dental implant therapy.

Intervention (I): AM iFDPs.

Comparison (C): SM iFDPs.

Outcome (O): Clinical performance including clinical, radiographic, aesthetic outcomes, survival and complication rates as well as patient-reported outcomes.

### 2.3 | Search strategy

An electronic search was conducted on Medline (PubMed) Embase, Cochrane Central, and Epistemonikos (for relevant systematic reviews addressing the topic). An electronic search was also performed on ClinicalTrial.gov and Cochrane Central Register of Controlled Trials for registered ongoing trials. The electronic search was conducted up to November 1, 2022 and designed and adapted to each type of database (Table 1). In addition, reference lists of retrieved studies for full-text screening and previous reviews on the topic were screened.

### 2.4 | Inclusion criteria

Randomized clinical trials (RCT), prospective and retrospective clinical studies, case series with at least 10 patients, and in vitro studies, all comparing AM to SM single- or multi-unit iFDPs.

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**TABLE 1** Search strategy.

| | |
|---|---|
| Medline | "dental implants"[MeSH Terms] OR "dental implants, single tooth"[MeSH Terms] OR "dental implants, single tooth"[MeSH Terms] OR "Dental Implantation, Endosseous"[MeSH Terms] OR "Dental Prosthesis" [MeSH Terms] OR "Dental Prosthesis, Implant-Supported" [MeSH Terms] OR "Denture, Partial, Fixed" [MeSH Terms] OR "Crowns" [MeSH Terms] OR "dental restoration failure" [MeSH Terms] OR "Tooth, Artificial" [MeSH Terms] OR "Dental abutments" [MeSH Terms] OR "restoration*" [All Fields] OR "suprastructure*" [All Fields] OR "crown*" [All Fields] OR "fixed dental prosthes*" [All Fields] OR "fixed partial denture*" [All Fields] OR "abutment*" [All Fields] OR "dental implant*"[All Fields] OR "Denture, Partial, Temporary" [MeSH Terms] AND Dental Technology [MeSH Terms] OR Computer-Aided Design [MeSH Terms] OR Computer-Aided Manufacturing [MeSH Terms] OR Manufacturing, Computer Aided [MeSH Terms] OR Design, Computer Aided [MeSH Terms] OR "CAD-CAM" [All Fields] AND Printing, Three Dimensional [MeSH Terms] OR Printings, Three-Dimensional [MeSH Terms] OR Three-Dimensional Printings [MeSH Terms] OR 3-Dimensional Printing [MeSH Terms] OR 3 Dimensional Printing [MeSH Terms] OR 3-Dimensional Printings [MeSH Terms] OR Printing, 3-Dimensional [MeSH Terms] OR Printings, 3-Dimensional [MeSH Terms] OR 3-D Printing [MeSH Terms] OR 3 D Printing [MeSH Terms] OR 3-D Printings [MeSH Terms] OR Printing, 3-D [MeSH Terms] OR Printings, 3-D [MeSH Terms] OR Three-Dimensional Printing [MeSH Terms] OR Three Dimensional Printing [MeSH Terms] OR 3D Printing [MeSH Terms] OR 3D Printings [MeSH Terms] OR Printing, 3D [MeSH Terms] OR Printing, 3D [MeSH Terms] OR "3-dimensional print*" [All Fields] OR "3d print*" [All Fields] OR "three-dimensional print*" [All Fields] OR "3-dimensional print*" [All Fields] OR "additive" [All Fields] OR "additive manufacturing" [All Fields] OR "additively manufact*"[All Fields] OR "CAD-CAM mill*" [All Fields] |
| Embase | "tooth implant"/exp OR "tooth implantation"/exp OR "implant-supported denture"/exp OR "tooth prosthesis"/exp OR "dental abutment"/exp OR "partial denture"/exp OR "prosthesis design"/exp OR "suprastructure*" OR "crown*" OR "fixed dental prosthes*" OR "fixed partial denture*" OR "abutment*" OR "dental implant*" AND "dental technology"/exp OR "computer aided design"/exp OR "computer aided design/computer aided manufacturing"/exp OR "CAD/CAM software"/exp OR "CAD-CAM" AND "three dimensional printing"/exp OR "three dimensional computer aided design"/exp OR "stereolithography"/exp OR "three dimensional printing" OR "additively manufact*" OR "3-dimensional print*" OR "additive" "OR additive manufacturing" OR "three-dimensional print*" OR "CAD-CAM mill*" |
| Central | [mh "dental implant"] OR "dental implant*" AND [mh "Computer-Aided Design"] OR [mh "Computer-Aided Manufacturing"] OR [mh "Manufacturing, Computer Aided"] OR [mh "Design, Computer Aided"] OR "CAD-CAM" OR "subtractive manufacturing" OR "subtractive manufact*" AND [mh "Printing, Three Dimensional"] OR [mh "Printings, Three-Dimensional"] OR [mh "Three-Dimensional Printings"] OR [mh "Three-Dimensional Printing"] OR [mh "Three Dimensional Printing"] OR "additive" OR "additive manufacturing" OR "additively manufact*" |
| Epistemonikos | "dental implants"[MeSH Terms] OR "dental implants, single tooth"[MeSH Terms] OR "dental implants, single tooth"[MeSH Terms] OR "Dental Implantation, Endosseous"[MeSH Terms] OR "Dental Prosthesis" [MeSH Terms] OR "Dental Prosthesis, Implant-Supported" [MeSH Terms] OR "Denture, Partial, Fixed" [MeSH Terms] OR "Crowns" [MeSH Terms] OR "fixed dental prosthes*" [All Fields] OR "fixed partial denture*" [All Fields] OR "abutment*" [All Fields] OR "dental implant*"[All Fields] OR "Denture, Partial, Temporary" [MeSH Terms] AND Computer-Aided Design [MeSH Terms] OR Computer-Aided Manufacturing [MeSH Terms] OR Manufacturing, Computer Aided [MeSH Terms] OR Design, Computer Aided [MeSH Terms] OR "CAD-CAM" [All Fields] AND Printing, Three Dimensional [MeSH Terms] OR Printings, Three-Dimensional [MeSH Terms] OR Three-Dimensional Printings [MeSH Terms] OR 3-Dimensional Printing [MeSH Terms] OR 3 Dimensional Printing [MeSH Terms] OR 3-Dimensional Printings [MeSH Terms] OR Printing, 3-Dimensional [MeSH Terms] OR Printings, 3-Dimensional [MeSH Terms] OR 3-D Printing [MeSH Terms] OR 3 D Printing [MeSH Terms] OR 3-D Printings [MeSH Terms] OR Printing, 3-D [MeSH Terms] OR Printings, 3-D [MeSH Terms] OR Three-Dimensional Printing [MeSH Terms] OR Three Dimensional Printing [MeSH Terms] OR 3D Printing [MeSH Terms] OR 3D Printings [MeSH Terms] OR Printing, 3D [MeSH Terms] OR Printing, 3D [MeSH Terms] OR "3-dimensional print*" [All Fields] OR "3d print*" [All Fields] OR "three-dimensional print*" [All Fields] OR "3-dimensional print*" [All Fields] OR "additive" [All Fields] OR "additive manufacturing" [All Fields] OR "additively manufact*"[All Fields] OR "CAD-CAM mill*" [All Fields] |

## 2.5 | Exclusion criteria

- Fully edentulous cases.
- Studies focusing on the manufacturing procedures of frameworks or abutments.

## 2.6 | Study selection

Based on the inclusion/exclusion criteria, two calibrated authors (JH; KP) screened independently the titles, abstracts, and full texts to check for eligibility. No restrictions were set for the date of publication, but the language for text eligibility was restricted to English, German, Spanish, Finnish, Turkish, Italian, and Portuguese. The identified articles were inserted into the Rayyan® Online Software (Qatar Computing Research Institute) and the duplicated articles were deleted. The inter-agreement among the authors was based on Cohen's Kappa score. Any disagreements were resolved by discussion with a third author (AI). All articles that did not meet the eligibility criteria were excluded and the reasons for exclusion were noted.

## 2.7 | Data extraction

Consistent with the latest handbook by the Cochrane group (Higgins et al., 2021) a paper form using processing software was used for the data extraction tables. The tables were pilot-tested by two extractors. Data were independently extracted by two reviewers (JH, KP) using data extraction tables (Excel Microsoft Corporation). In case of missing data, the authors of the included studies were contacted via email to provide the missing or additional data.

## 3 | RESULTS

### 3.1 | Search

A total of 2′184 articles were identified through the electronic search (Figure 1). After the removal of 414 duplicates, 1′770 titles were screened, and 23 records were evaluated on the basis of their abstract and on the information available in the trial registry. Based on full-text analysis 15 articles were excluded (Table 2). Two relevant trial registrations (German Clinical Trial Register ID: DRKS00029049 and Brazilian Registry of Clinical Trials ID: RBR-4msyxn) were further excluded, as the final reports were not available. A total of 6 articles remained and were finally included. The inter-rater agreement during the selection of the abstracts (screening phase) between reviewers was $\kappa = 0.839$.

### 3.2 | Description of included studies and study characteristics

The included studies were published between 2016 and 2022 (Table 3, Figure 2). No clinical studies could be found and, therefore, only in vitro studies were included. A total of 6 in-vitro studies including screw- or cement-retained single-unit iFDPs were analyzed. Performance was evaluated by assessing marginal and internal discrepancies and mechanical properties (fracture loads, bending moments). Materials included for the AM iFDPs were ceramics (zirconia) and polymers (PMMA, resin composite). For the SM iFDPs, zirconia, lithium disilicate reinforced glass ceramic, resin-modified ceramic, composite, and polymer materials (PMMA, Pekkton) were investigated in the included studies. The used AM methods were digital light processing (DLP) and stereolithography (SLA). SM refers to milling processes with multi-axis milling machines.

No clinical studies comparing AM to SM iFDPs were found. The identified in vitro investigations comparing these two manufacturing methods for iFDPs focused on (1) the marginal and internal discrepancies, and (2) the fracture loads and bending moments.

The data were analyzed qualitatively and given that no clinical study was included no demographics were reported. Considering

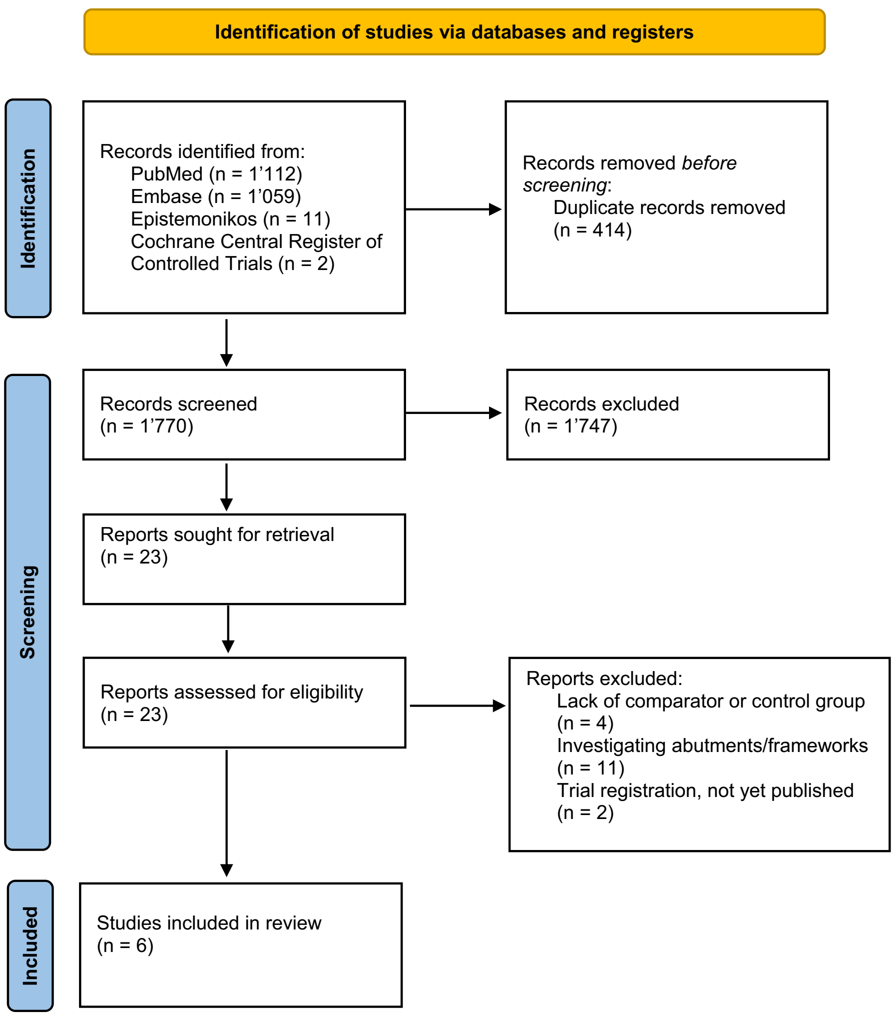


FIGURE 1 Flow chart of the systematic review.

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**TABLE 2** List of excluded studies.

| Author/Publication Year | Journal | Reason for exclusion |
|---|---|---|
| Kim et al. (2017) | Materials | Investigating abutments/ frameworks |
| Akcin et al. (2018) | The Journal of Prosthetic Dentistry | Investigating abutments/ frameworks |
| Obermeier et al. (2018) | Clinical Oral Investigations | Lack of comparator or control group |
| Svanborg et al. (2018) | The International Journal of Oral and Maxillofacial Implants | Investigating abutments/ frameworks |
| Ghodsi et al. (2019) | European Journal of Dentistry | Investigating abutments/ frameworks |
| Presotto et al. (2019) | The Journal of Prosthetic Dentistry | Investigating abutments/ frameworks |
| Barbin et al. (2020) | Journal of the Mechanical Behaviour of Biomedical Materials | Investigating abutments/ frameworks |
| Gonzalo et al. (2020) | Materials | Investigating abutments/ frameworks |
| Kim and Lee (2020) | BioMed Research International | Lack of comparator or control group |
| Williams et al. (2020) | Journal of Oral and Maxillofacial Surgery | Lack of comparator or control group |
| Yildirim (2020) | The Journal of Prosthetic Dentistry | Investigating abutments/ frameworks |
| Graf et al. (2021) | The Journal of Advanced Prosthodontics | Lack of comparator or control group |
| Revilla-Leon et al. (2021) | The Journal of Prosthetic Dentistry | Investigating abutments/ frameworks |
| Hsu et al. (2022) | Polymers | Investigating abutments/ frameworks |
| Revilla-Leon et al. (2022) | Journal of Prosthodontics | Investigating abutments/ frameworks |

that only in vitro studies were included, no risk of bias analysis was deemed necessary.

### 3.3 | Data extraction and management

Two reviewers (KP and JH) extracted data from the included studies using a pre-piloted data extraction form and checked them against each other. We resolved any disagreements by discussion or with a third review author (AI). We extracted data on: Author, date of publication, study design, manufacturing technique in AM and SM, testing method, marginal and internal discrepancies, fracture load, and bending moments.

### 3.4 | Marginal and internal discrepancies

Three of the included studies examined the marginal and internal discrepancies between AM and SM iFDPs. One of these studies assessed interim iFDPs, while two examined definitive iFDPs.

An in vitro study compared cemented interim single-unit iFDPs, which were manufactured either using a 4-axis milling machine (SM) or DLP (AM) (Park et al., 2016). The used materials were Pekkton (SM) and PMMA (AM). The marginal and internal discrepancies between the prostheses and the standardized implant abutments were examined at 20 reference points. The mean marginal discrepancies (±standard deviations) amounted to 58.02 (±19.75) µm (SM) and 56.85 (±22.24) µm (AM). For both groups, the largest internal discrepancies were measured in the occlusal area with mean values (±standard deviations) of 197.87 (±42.18) µm for SM and 167.81 (±41.86) µm for AM. Statistically significant differences between AM and SM for the intermarginal and occlusal areas were reported, while the marginal, axio-gingival, and axio-occlusal discrepancies did not reach statistically significant levels.

The second study examining the marginal and internal discrepancies, compared three study groups (Revilla-Leon, Methani, et al., 2020). In the SM group, definitive single-unit SM zirconia iFDPs were tested. The second group consisted of definitive single-unite AM zirconia iFDPs (AM full-contour). In the third group, the

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**TABLE 3** Characteristics of included studies.

| Author/Publication Year | Journal | Study design | Number of specimens per group | Material test group (AM) | Manufacturing technique test group (AM) | Materials control group (SM) | Manufacturing techniques control group (SM) | Testing method | Primary outcome | Results |
|---|---|---|---|---|---|---|---|---|---|---|
| **Studies about marginal and internal discrepancies** | | | | | | | | | | |
| Park et al. (2016) | The Journal of Prosthetic Dentistry | In vitro | 40 | PMMA (E-Dent; Envision TEC) | Digital light processing (Perfactory PixCera; Envision TEC) | Pekkton (Pekkton Ivory; Cendres&Metaux) | 4-axis milling machine (Cendres&Metaux SA) | Silicon replica method | Marginal and internal discrepancies | Mean discrepancy (μm) (±SD)<br>marginal<br>SM 58.02 (±19.75)<br>AM 56.85 (±22.24)<br>intermarginal<br>SM 96.70 (±25.38)<br>AM 108.50 (±35.21)<br>axio-gingival<br>SM 67.02 (±17.97)<br>AM 67.54 (±20.29)<br>axio-occlusal<br>SM 81.41 (±30.64)<br>AM 79.57 (±28.35)<br>occlusal<br>SM 197.87 (±42.18)<br>AM 167.81 (±41.86)<br>total<br>SM 109.59 (±71.53)<br>AM 96.05 (±50.23) |
| Revilla-Leon, Methani, et al. (2020) | The Journal of Prosthetic Dentistry | In vitro | 10 | Zirconia stabilized with 3% yttria (3DMix ZrO2 paste; 3DCeram Co) | Stereolithography (CERAMAKER 900; 3DCeram Co) | CARES Zirconia-dioxide (Institut Straumann AG) | 5-axis milling machine (CARES Straumann centralized) | Silicon replica method | Marginal and internal discrepancies | Median discrepancy (μm) (±SD):<br>marginal<br>SM 37.5 (±50)<br>AM full-contour 146.0 (±103.2)<br>AM splinted 79.5 (±49.2)<br>internal<br>SM 73.0 (±44.7)<br>AM full-contour 79.0 (±46)<br>AM splinted 85.0 (±48) |
| **Studies about marginal and internal discrepancies and mechanical properties** | | | | | | | | | | |
| Donmez et al. (2022) | Journal of Dentistry | In vitro | 10 | Composite resin Saremco Print, Crowntec (SP) | Digital light processing (MAX UV; ASIGA) | Composite resins (Brilliant, Crios) (BC), (Cerasmart 270) (CS)/Resin-modified ceramic (Vita Enamic) (VE) | 4-axis milling machine (inLab MC XL; Dentsply Sirona) | Stereomic-roscopical measuring of marginal gap; static loading | Marginal discrepancy; fracture load | Mean marginal discrepancy (μm) (±SD) after cementation:<br>SM BC 63.3 (±2.8)<br>SM VE 65.5 (±2.7)<br>SM CS 62.6 (±3.5)<br>AM 52.4 (±2.3)<br>Mean fracture loads (N) (±SD):<br>SM BC 1′333.23 (±144.73)<br>SM VE 1′359.25 (±159.63)<br>SM CS 1′274.32 (±135.8)<br>AM 1′413.91 (±140.49) |

(Continues)

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TABLE 3 (Continued)

| Author/Publication Year | Journal | Study design | Number of specimens per group | Material test group (AM) | Manufacturing technique test group (AM) | Materials control group (SM) | Manufacturing techniques control group (SM) | Testing method | Primary outcome | Results |
|---|---|---|---|---|---|---|---|---|---|---|
| **Studies about mechanical properties** | | | | | | | | | | |
| Martin-Ortega et al. (2022) | The Journal of Prosthetic Dentistry | In vitro | 10 | Photopolymer interim dental resin (SHERAprint-cb; Shera) | Digital light processing 3D printer (SHERAprint30; Shera) | PMMA (Vivodent CAD Multi; Ivoclar) | 5-axis milling machine (PrograMill CAM V4; Ivoclar) | Aging, static loading | Fracture load | Mean fracture loads (N) (±SD): anterior SM 988 (±55) AM 636 (±277) posterior SM 424 (±68) AM 321 (±129) |
| Sudbeck et al. (2022) | Dental Materials | In vitro | 12 | 3D Printed resin (Next Dent) | Digital light processing (D 20II, Rapidshape) | Composite resin (Crios Coltene) (CC)/ Resin-modified ceramic (Vita Enamic) (VE)/ PMMA (Ceramill A-Temp) (PM) with and without titanium base | 5-axis milling machine (Ceramill Motion 2, Amann Girrbach) | Aging, dynamic, and static loading | Bending moment | Mean bending moment (Ncm)/ fracture load (N) after aging (±SD): with titanium base SM CC 775 (±189)/1′565 (±381) SM VE 676 (±108)/1′365 (±218) SM PM 622 (±109)/1′258 (±219) AM 520 (±131)/1′050 (±264) without titanium base SM CC 510 (±325)/1′029 (±657) SM VE 611 (±124)/1′236 (±250) SM PM 456 (±22)/921 (±44) AM 563 (±96)/1′138 (±194) |
| Zandinejad et al. (2019) | Journal of Prosthodontics | In vitro | 10 | Zirconia stabilized with 3% yttria (3DMix ZrO2 paste; 3DCeram Co.) (Zr) | Stereolithography (CeraMaker 900; 3DCeram Co.) | Zirconia (Lava Plus Zirconia W1, 3M Co.) (ZR)/Lithium disilicate (IPS e.max CAD; Ivoclar Vivadent) (LiSi) | 5-axis milling machine (CARES Straumann centralized) | Static loading | Fracture load | Median fracture loads (N): SM Zr 1′292 (±189) SM LiSi 1′289 (±142) AM Zr 1′243.4 (±265.5) |

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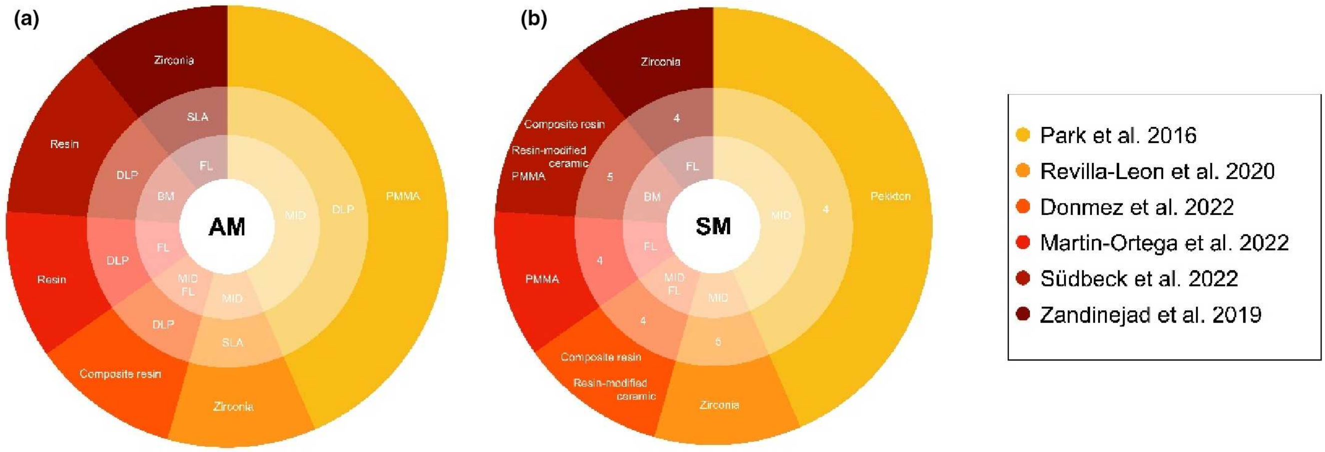


**FIGURE 2** Graphical overview of the characteristics of the included in vitro studies for the groups AM (a) and SM (b). For the AM groups, the restorative materials, the fabrication method (DLP, SLA) and the measurement methods (BM = bending moments, FL = fracture loads, MID = marginal and internal discrepancy) are indicated from the outside to the inside. For the SM groups, the restorative materials, the number of milling axes (4, 5) and the measuring methods (BM, FL, MID) are indicated from the outside to the inside.

full-contour design was divided into two files: one representing the enamel part of the iFDP and the second one the dentin part. Only the latter was further processed to be fabricated by AM technologies to build the third group under investigation (AM splinted). For the AM of the zirconia parts, SLA was applied. The SM and AM fabricated zirconia parts were placed onto individualized zirconia abutments to measure the marginal and internal discrepancies. The silicon replica technique was used to determine the marginal discrepancies at 25 points and the internal discrepancies at 50 points per specimen. Median marginal discrepancies (±standard deviations) of 37.5 (±50) μm (SM), 146.0 (±103.2) μm (AM full-contour), and 79.5 (±49.2) μm (AM splinted) were found. In the internal areas, discrepancies of 73.0 (±44.7) μm (SM), 79.0 (±46) μm (AM full-contour), and 85.0 (±48) μm (AM splinted) were detected. The differences of marginal discrepancies were significantly different when comparing AM full-contour to AM splinted and SM, and when comparing AM splinted to SM. As for the internal discrepancies, the differences between the groups were statistically significant when comparing SM to AM full-contour and splinted and when comparing AM full-contour to AM splinted.

In another in vitro study, the marginal discrepancy for definitive single-unit iFDPs, where the prostheses were cemented to standardized titanium abutments, was investigated using stereomicroscopy (Donmez & Okutan, 2022). For the fabrication of the SM iFDPs, three different definitive restorative materials were used, including two composites and one resin-modified ceramic material. The iFDPs were milled using a 4-axis milling machine. For the AM group, DLP was used for the fabrication of definitive composite resin iFDPs. Marginal discrepancy measurements were performed at 60 points per iFDP before and after cementation with self-adhesive resin cement. The mean marginal discrepancies (±standard deviations) after cementation amounted to 62.6–65.5 μm in the SM groups and 52.4 (±2.3) μm in the AM group. The results showed significantly lower marginal discrepancy values for the AM specimens compared to the SM groups.

## 3.5 | Mechanical properties: fracture loads and bending moments

Four of the included studies examined the mechanical properties of SM and AM iFDPs—all single-unit—measuring the fracture loads (four studies) and the bending moments (one study). One of the studies evaluated interim iFDPs, while two assessed definitive iFDPs. One study evaluated both definitive and interim materials.

An included study (Donmez & Okutan, 2022) compared the fracture resistance of an AM composite resin with three different SM materials: two composites and a resin-modified ceramic. The used AM technique was DLP. The definitive prostheses were cemented to titanium abutments using a self-adhesive resin cement and then statically loaded with a vertical force. In the SM groups mean fracture loads of 1′274–1′359N were found, whereas the AM group showed a mean value (±standard deviations) of 1′413.91 (±140.49) N. All the iFDPs fractured without an abutment fracture and the results showed no significant differences between the groups.

A further study (Martin-Ortega et al., 2022) evaluated the fracture loads of anterior and posterior polymer-based screw-retained interim iFDPs. The SM PMMA iFDPs were fabricated using a 5-axis milling machine. The AM fabrication process for the polymer iFDPs was DLP. All prostheses were cemented to standardized metallic implant abutments and screw-retained to the implants. Prior to loading, all specimens were subjected to thermo-cyclic aging. The mean fracture loads (±standard deviations) were 988 (±55) (SM) and 636 (±277) N (AM) for the anterior iFDPs, whereas the posterior groups showed values of 424 (±68) (SM) and 321 (±129) N (AM). The fracture load testing resulted in fractures of the iFDPs, while the abutments remained intact. The failure modes consisted of multiple fractures in the anterior group and mostly single longitudinal fractures in the posterior group. The results showed significantly higher failure load values for the SM iFDPs in both the anterior and posterior groups.

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In both manufacturing methods, the anterior iFDPs had higher mean fracture load values than the posterior iFDPs.

Another included study (Zandinejad et al., 2019) compared the fracture loads of definitive SM (5-axis milling machine) zirconia and lithium disilicate iFDPs to SLA AM zirconia iFDPs. All prostheses were cemented to standardized zirconia abutments. The antagonist for the loading test consisted of a Co-Cr prosthesis. The median fracture loads (±standard deviations) were 1′292 (±189) N (SM Zirconia), 1′289 (±142) N (SM lithium disilicate), and 1′243 (±265.5) N (AM). No significant differences were found among the groups. All fractures occurred at the abutment level with the fracture line near the interface of the implant analog and the zirconia abutment. Therefore, all iFDPs were intact at the end of the loading test.

One study (Sudbeck et al., 2022) reporting on mechanical properties evaluated the bending moments and fracture loads of polymer-based iFDPs with or without a standardized titanium base before and after aging. For the specimens with a titanium base, the prostheses were cemented onto the titanium base and screw-retained to the implant. For the specimens without a titanium base, the iFDPs were directly screwed to the implant. The manufacturing methods included milling with a 5-axis milling machine and DLP. The tested materials included composite resin, resin-modified ceramic, PMMA, and a 3D-printed resin. Before aging, the iFDPs with a titanium base showed no significant differences in bending moments for any of the restorative materials tested. iFDPs without a titanium base exhibited higher bending moments when fabricated using 3D printed resin and milled composite resin compared to the other materials before aging. After aging, in the titanium base group, 3D printed resin resulted in lower bending moments than milled composite resin. Without a titanium base, there was no significant impact of the restorative material on the results after aging. The results for the fracture loads showed no significant differences between the materials when titanium base abutments were not used. With a titanium base abutment AM iFDPs had the lowest fracture load values.

# 4 | DISCUSSION

## 4.1 | Main findings

The current systematic review sought to compare and report on the performance of AM and SM iFDPs. No clinical studies could be found that directly compared the two methods of fabrication. Based on the included in vitro studies, the present systematic review revealed:

1. A lack of studies comparing the performance of AM and SM iFDPs.
2. No significant differences between AM and SM interim iFDPs for marginal discrepancies. The internal discrepancies were statistically significantly lower with AM compared to SM only in inter-marginal and occlusal areas.
3. Inconsistent results when comparing marginal and internal discrepancies of SM versus AM definitive iFDPs.
4. Lower fracture loads and bending moment values for AM compared to SM interim iFDPs.
5. Similar fracture loads for AM and SM definitive iFDPs.
6. Insufficient data to draw strong conclusions.
7. Considerable heterogeneity across the studies limiting a thorough comparison. Confounding variables included the type of prosthesis (definitive or interim), the varying materials, the different locations, and the lack of detailed information regarding material compositions, production, and post-processing parameters.

## 4.2 | Marginal and internal discrepancies

When examining the marginal and internal discrepancies between a prosthesis and an abutment, the marginal fit plays a pivotal role. Consequently, the accuracy in the marginal area is a relevant aspect of the longevity of indirect prostheses and thus the clinical success of iFDPs. A lack of marginal fit may expose the prosthesis/abutment interface to the oral environment, increasing the possibility of bacterial colonization and triggering peri-implant inflammation, which can eventually may lead to marginal bone loss (Broggini et al., 2003). Furthermore, a poor fit can predispose to plaque accumulation, intensifying the ensuing inflammatory response. Clinically, the marginal gap between the restorative material and the abutment is usually filled up with resin cement (Ioannidis et al., 2020; Pitta et al., 2021). It is known that this interface area can be further affected by aging processes (Ioannidis et al., 2020). In the literature, a mean marginal discrepancy of <120 μm has been reported as clinically acceptable (Jemt & Book, 1996), while other authors have reported a misfit of up to 200 μm as an acceptable discrepancy (Boeckler et al., 2005). The present review found similar marginal accuracies of interim iFDPs between SM and AM when using Pekkton and PMMA as restorative materials (Park et al., 2016). This suggests that AM could be a viable alternative to SM for iFDPs. The study had a high number of specimens per group, which increased the statistical power and enabled the detection of small differences. When it comes to definitive iFDPs, the present review found conflicting results on the marginal and internal discrepancies between AM and SM fabrication methods. Whereas some results favored the SM method (Revilla-Leon, Methani, et al., 2020), another study showed significantly lower marginal discrepancies for the AM fabricated prostheses (Donmez & Okutan, 2022). The differences in outcomes might be attributed to the use of different restorative materials and manufacturing technologies. Resin-based and resin-modified ceramic materials showed lower marginal discrepancies for AM specimens than for SM groups. Resin-based materials can be fabricated with SM or AM technologies at a high precision (Jockusch & Ozcan, 2020; No-Cortes et al., 2022; Revilla-Leon & Ozcan, 2019). In contrast, the study showing non-clinically acceptable marginal and internal accuracies for full-contour prostheses fabricated by AM technologies used zirconia as restorative material (Revilla-Leon, Methani, et al., 2020). The latter study showed only acceptable marginal and internal discrepancies for the AM process for the group testing the AM intermediate secondary

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abutment (AM splinted). The anatomically full-contoured and the splinted prostheses did not differ regarding the design of the cervical area. However, the total volume of the AM splinted prostheses was substantially smaller. Other studies confirm the acceptable marginal accuracy when small-volume prostheses are fabricated (Ioannidis et al., 2021). Accordingly, the authors speculated that differences in the material bulk or volume design might lead to varying directions and volumetric shrinkage behavior during the post-processing, causing the accuracy differences between the 2 AM groups (Revilla-Leon, Methani, et al., 2020). This might be further explained by the fact that zirconia prostheses manufactured in full contour showed a high standard deviation in discrepancies in the marginal area.

The included studies indicate that marginal discrepancies might pose a challenge in the manufacturing process of the iFDPs. Although the discrepancies found may be partially clinically acceptable, the results of AM groups tended to be more variable (Revilla-Leon, Methani, et al., 2020). This might be explained by the further development of SM. AM, on the contrary, has only been recently introduced in dentistry for the fabrication of prostheses. A further aspect that needs to be taken into consideration when interpreting the present findings is the method of assessment. Whilst some studies performed a two-dimensional cross-sectional analysis, others performed a direct analysis of the marginal area using a stereomicroscope. Arguably, a 3D analysis of the complete prosthesis might be necessary to generate accurate information regarding the marginal and internal fit (Boitelle et al., 2018). Additionally, more information about the production parameters, debinding, sintering, and post-processing procedures for the SM and AM techniques would have been needed to further interpret the data. This is of importance since these factors can influence the final accuracy of the prostheses and therefore determine the marginal and internal fit (Komissarenko et al., 2018; Tian et al., 2021). Detailed information on the material composition for the print materials was mostly lacking. At this stage, there is insufficient data to draw strong conclusions on the marginal fit of AM compared to SM iFDPs.

## 4.3 | Fracture loads and bending moments

The mechanical properties play a pivotal crucial in the clinical success of iFDPs. Factors such as fracture loads and bending moments are important and determine whether a prosthesis can withstand the physiological occlusal forces. The present review found lower fracture loads and bending moment values for AM compared to SM interim iFDPs (Martin-Ortega et al., 2022). While interim AM iFDPs in the anterior region might withstand physiological forces, posterior ones could have a higher risk for fractures (Martin-Ortega et al., 2022). The AM iFDPs showed higher standard deviations compared to the SM ones. In other words, there was more variability in the results. AM iFDPs showed failure modes with several smaller fragments, whereas the iFDPs in the SM groups mainly fractured in two to four pieces (Sudbeck et al., 2022). Two of the included studies evaluated screw-retained iFDPs (Martin-Ortega et al., 2022; Sudbeck et al., 2022). It should be noted that the screw access channel might have affected the manufacturing accuracy as well as the mechanical properties. Also, artificial aging led to a decrease in bending moment values (Sudbeck et al., 2022).

As for definitive iFDPs, the present review found a similar fracture load for AM and SM iFDPs. These findings should, however, be interpreted with caution because of the varying manufacturing methodology applied, including printer, printing protocol, and restorative materials. For example, in one of the included studies, all specimens were fractured at the abutment level but none at the level of the prosthesis (Zandinejad et al., 2019). Therefore, the results cannot provide a real comparison between the tested manufacturing methods, but demonstrate that all included restorative materials were able to withstand physiological occlusal forces. In fact, previous studies (Martin-Ortega et al., 2022; Park et al., 2019) have evaluated the mechanical properties of AM prostheses but the varying methodology applied, for example, manufacturing technique, materials used, and methods of assessment, made it difficult to draw definitive conclusions (Giugovaz et al., 2022). In addition, aging processes were often lacking in the included studies. The influence of aging processes could have a significant impact on the fracture load and should therefore be included in further study designs to have a more complete picture (Sudbeck et al., 2022). Detailed information on the material compositions, printing parameters, sintering processes, and postprocessing procedures was often lacking.

Fracture loads and bending moments are primarily material parameters and are highly influenced by the mechanical properties of the restorative material (Donmez et al., 2022). The manufacturing process (AM and SM) may have a secondary effect on the mechanical properties of the iFDPs. However, the extent to which the manufacturing process affects the resulting bending moments or fracture loads remains unclear. Therefore, the direct comparisons of mechanical performance are a result of the material properties themselves and the associated manufacturing processes.

## 4.4 | Further aspects regarding AM procedures

The AM techniques used in the included studies were SLA and DLP. The main difference between stereolithography and digital light processing is the light source. The differences in manufacturing techniques might have contributed to the differences found across the studies. A narrative review evaluating AM techniques in prosthodontics considered SLA the most accurate technique (Alharbi et al., 2017). The precision of the SLA method is determined by different factors such as the precision of the laser beam position, the exposure size in x–y planes, and the resolution in the *z*-axis (Alharbi et al., 2017). The precision of the DLP method is determined by different factors such as the optical specifications of the DMD, lens quality, pixel size, and resolution (Alharbi et al., 2017). Additionally, there are differences in accuracy between the available 3D printers. There are also different parameters, including the layer thickness

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and printing orientation, that can have an influence on the printing results (Alharbi et al., 2017).

Another important point to consider when interpreting the present findings is the restorative material used as this can influence the clinical outcomes. In this sense, it should be mentioned that the AM process is not equally evolved for all materials. While studies show good results with the use of metals, the AM of ceramics and polymers still has some limitations (Hesse & Ozcan, 2021; Jockusch & Ozcan, 2020; Revilla-Leon, Meyer, & Ozcan, 2019). The AM processes of included studies (SLA and DLP) can be used to produce ceramic parts by mixing ceramic powders and photosensitive resin. Green parts are then fabricated using the vat photopolymerization. Subsequently, during the debinding and sintering processes the organic materials in photosensitive resin are eliminated, and the ceramic particles are fused together to create denser ceramic objects (Revilla-Leon, Meyer, et al., 2020). An in vitro study comparing the fracture resistance and flexural strength of SM and AM zirconia bars resulted in significantly lower values for the AM parts indicating that the mechanical properties of printed zirconia might still be a limiting factor. AM zirconia seems to be more sensitive to shrinkage during the sintering process. A review evaluating the AM of dental ceramics reported favorable volumetric shrinkage for SM compared to AM (Al Hamad et al., 2022). That review also reported that an increase in the zirconia content of a suspension could lead to reduced volumetric shrinkage, whereas it might have challenging effects on factors such as the viscosity and layer thickness. This aspect could be further evaluated to overcome the limitations for AM zirconia prostheses. As for the use of polymers, based on the included studies it appears that AM of interim resin iFDPs is a reliable method and different kinds of geometries can be manufactured. Mechanically AM resin material seems to be more prone to fractures compared to other resin materials. One of the limiting factors may be the lower elastic modulus for the polymers used in AM procedures. A recent review concluded that there was a lack of dental polymers, which could remain in the oral cavity for a longer period than 12 months (Goodridge et al., 2012; Jockusch & Ozcan, 2020; Sudbeck et al., 2022).

Further studies are needed to compare AM and SM procedures and thus increase the evidence. Similar materials should be used for both manufacturing processes to enable clearer comparisons. Additionally, detailed documentation of material compositions and manufacturing processes is required for comparisons with other studies. Other in vitro studies are necessary to investigate the potential advantages of AM, such as the inclusion different material properties or colors in the same workpiece. This aspect was not addressed in the current studies and could offer more possibilities than the SM process. Randomized clinical trials are needed to compare the clinical performance of AM and SM iFDPs.

The low number of studies included, and the absence of clinical studies limit the translation of findings to the clinic. Interestingly, the present systematic review indicate that interim AM iFDPs in the anterior region might be clinically acceptable in terms of fit and mechanical properties, making them a viable alternative to SM processes and resulting in reduced material waste. However, the use of AM iFDPs is still insufficiently investigated and should not be widely used in clinical practice outside of clinical trials.

The major strength of the present review is the comprehensive search and the adherence to the methodological standards through all stages of the review process. The comprehensive search was achieved by means of searching additional clinical trial registers. The present review, however, also has limitations, particularly the lack of clinical studies, as no clinical study could be found comparing AM and SM iFPDs, and thus only in vitro in studies were included. Hence, the outcomes of the review could not answer the original question posed. In addition, the absence of a grey literature search and the language restriction to English, German, Spanish, Finnish, Turkish, and Portuguese may have prevented the inclusion of additional studies. Finally, relevant factors including the material compositions and (post-) processing parameters, were not always available limiting the comparability between the studies.

## 5 | CONCLUSION

At present, there is very limited in vitro and no clinical data available comparing additively manufactured (AM) fixed implant-supported dental prostheses (iFDPs) with those fabricated using subtractive manufacturing (SM) techniques. Heterogeneity across the available and included in vitro studies delivered insufficient data to draw conclusions on the marginal and internal discrepancies and the mechanical performance. Therefore, the performance and comparison of AM iFDPs with those fabricated by SM procedures remain to be elucidated.

### AUTHOR CONTRIBUTIONS

All authors have made substantial contributions to conception and design of the study. FJS, JH, KP were involved in data collection and data analysis. AI, KP, and FJS interpreted the data and drafted the manuscript. All authors critically revised the draft and approved the final version.

### CONFLICT OF INTEREST STATEMENT

This study was financially supported by the Clinic for Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Zurich, Switzerland.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## REFERENCES


Akcin, E. T., Guncu, M. B., Aktas, G., & Aslan, Y. (2018). Effect of manufacturing techniques on the marginal and internal fit of cobalt-chromium implant-supported multiunit frameworks. *The Journal of Prosthetic Dentistry*, *120*(5), 715–720. https://doi.org/10.1016/j.prosdent.2018.02.012

Al Hamad, K. Q., Al-Rashdan, B. A., Ayyad, J. Q., Al Omrani, L. M., Sharoh, A. M., Al Nimri, A. M., & Al-Kaff, F. T. (2022). Additive manufacturing of dental ceramics: A systematic review and meta-analysis. *Journal of Prosthodontics*, *31*(8), e67–e86. https://doi.org/10.1111/jopr.13553

Al-Dwairi, Z. N., Alkhatatbeh, R. M., Baba, N. Z., & Goodacre, C. J. (2019). A comparison of the marginal and internal fit of porcelain laminate veneers fabricated by pressing and CAD-CAM milling and cemented with 2 different resin cements. *Journal of Prosthetic Dentistry*, *121*(3), 470–476. https://doi.org/10.1016/j.prosdent.2018.04.008

Alharbi, N., Osman, R. B., & Wismeijer, D. (2016). Factors influencing the dimensional accuracy of 3D-printed full-coverage dental restorations using stereolithography technology. *The International Journal of Prosthodontics*, *29*(5), 503–510. https://doi.org/10.11607/ijp.4835

Alharbi, N., Wismeijer, D., & Osman, R. B. (2017). Additive manufacturing techniques in prosthodontics: Where do we currently stand? A critical review. *The International Journal of Prosthodontics*, *30*(5), 474–484. https://doi.org/10.11607/ijp.5079

Barbin, T., Veloso, D. V., Del Rio Silva, L., Borges, G. A., Presotto, A. G. C., Barao, V. A. R., & Mesquita, M. F. (2020). 3D metal printing in dentistry: An in vitro biomechanical comparative study of two additive manufacturing technologies for full-arch implant-supported prostheses. *Journal of the Mechanical Behavior of Biomedical Materials*, *108*, 103821. https://doi.org/10.1016/j.jmbbm.2020.103821

Boeckler, A. F., Stadler, A., & Setz, J. M. (2005). The significance of marginal gap and overextension measurement in the evaluation of the fit of complete crowns. *The Journal of Contemporary Dental Practice*, *6*(4), 26–37.

Boitelle, P., Tapie, L., Mawussi, B., & Fromentin, O. (2018). Evaluation of the marginal fit of CAD-CAM zirconia copings: Comparison of 2D and 3D measurement methods. *The Journal of Prosthetic Dentistry*, *119*(1), 75–81. https://doi.org/10.1016/j.prosdent.2017.01.026

Broggini, N., McManus, L. M., Hermann, J. S., Medina, R. U., Oates, T. W., Schenk, R. K., Buser, D., Mellonig, J., & Cochran, D. L. (2003). Persistent acute inflammation at the implant-abutment interface. *Journal of Dental Research*, *82*(3), 232–237. https://doi.org/10.1177/154405910308200316

De Angelis, P., Passarelli, P. C., Gasparini, G., Boniello, R., D'Amato, G., & De Angelis, S. (2020). Monolithic CAD-CAM lithium disilicate versus monolithic CAD-CAM zirconia for single implant-supported posterior crowns using a digital workflow: A 3-year cross-sectional retrospective study. *The Journal of Prosthetic Dentistry*, *123*(2), 252–256. https://doi.org/10.1016/j.prosdent.2018.11.016

Donmez, M. B., Diken Turksayar, A. A., Olcay, E. O., & Sahmali, S. M. (2022). Fracture resistance of single-unit implant-supported crowns: Effects of prosthetic design and restorative material. *Journal of Prosthodontics*, *31*(4), 348–355. https://doi.org/10.1111/jopr.13415

Donmez, M. B., & Okutan, Y. (2022). Marginal gap and fracture resistance of implant-supported 3D-printed definitive composite crowns: An in vitro study. *Journal of Dentistry*, *124*, 104216. https://doi.org/10.1016/j.jdent.2022.104216

Galante, R., Figueiredo-Pina, C. G., & Serro, A. P. (2019). Additive manufacturing of ceramics for dental applications: A review. *Dental Materials*, *35*(6), 825–846. https://doi.org/10.1016/j.dental.2019.02.026

Ghodsi, S., Alikhasi, M., & Soltani, N. (2019). Marginal discrepancy of single implant-supported metal copings fabricated by various CAD/CAM and conventional techniques using different materials. *European Journal of Dentistry*, *13*(4), 563–568. https://doi.org/10.1055/s-0039-1700364

Gintaute, A., Weber, K., Zitzmann, N. U., Bragger, U., Ferrari, M., & Joda, T. (2021). A double-blind crossover RCT analyzing technical and clinical performance of monolithic ZrO2 implant fixed dental prostheses (iFDP) in three different digital workflows. *Journal of Clinical Medicine*, *10*(12), 2661. https://doi.org/10.3390/jcm10122661

Giugovaz, A., Perez-Giugovaz, M. G., Al-Haj Husain, N., Barmak, A. B., Ozcan, M., & Revilla-Leon, M. (2022). Flexural strength of aged and nonaged interim materials fabricated by using milling, additive manufacturing, and a combination of subtractive and additive methods. *The Journal of Prosthetic Dentistry*, *128*(3), 513 e511. https://doi.org/10.1016/j.prosdent.2022.05.004

Gonzalo, E., Vizoso, B., Lopez-Suarez, C., Diaz, P., Pelaez, J., & Suarez, M. J. (2020). Evaluation of milled titanium versus laser sintered Co-Cr abutments on the marginal misfit in internal implant-abutment connection. *Materials*, *13*(21), 4873. https://doi.org/10.3390/ma13214873

Goodridge, R. D., Tuck, C. J., & Hague, R. J. M. (2012). Laser sintering of polyamides and other polymers. *Progress in Materials Science*, *57*(2), 229–267. https://doi.org/10.1016/j.pmatsci.2011.04.001

Graf, T., Guth, J. F., Diegritz, C., Liebermann, A., Schweiger, J., & Schubert, O. (2021). Efficiency of occlusal and interproximal adjustments in CAD-CAM manufactured single implant crowns – Cast-free vs 3D printed cast-based. *Journal of Advanced Prosthodontics*, *13*(6), 351–360. https://doi.org/10.4047/jap.2021.13.6.351

Hesse, H., & Ozcan, M. (2021). A review on current additive manufacturing technologies and materials used for fabrication of metal-ceramic fixed dental prosthesis. *Journal of Adhesion Science and Technology*, *35*(23), 2529–2546. https://doi.org/10.1080/01694243.2021.1899699

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (Eds.). (2021). *Cochrane Handbook for Systematic Reviews of Interventions* version 6.2 (updated February 2021). www.training.cochrane.org/handbook

Hsu, W. C., Peng, T. Y., Kang, C. M., Chao, F. Y., Yu, J. H., & Chen, S. F. (2022). Evaluating the effect of different polymer and composite abutments on the color accuracy of multilayer pre-colored zirconia polycrystal dental prosthesis. *Polymers*, *14*(12), 2325. https://doi.org/10.3390/polym14122325

Ioannidis, A., Gil, A., Hammerle, C. H., Jung, R. E., Zinelis, S., & Eliades, G. (2020). Effect of thermomechanical loading on the cementation interface of implant-supported CAD/CAM crowns luted to titanium abutments. *International Journal of Prosthodontics*, *33*(6), 656–662. https://doi.org/10.11607/ijp.6709

Ioannidis, A., Park, J. M., Husler, J., Bomze, D., Muhlemann, S., & Ozcan, M. (2021). An in vitro comparison of the marginal and internal adaptation of ultrathin occlusal veneers made of 3D-printed zirconia, milled zirconia, and heat-pressed lithium disilicate. *Journal of Prosthetic Dentistry.*, *128*, 709–715. https://doi.org/10.1016/j.prosdent.2020.09.053

Jemt, T., & Book, K. (1996). Prosthesis misfit and marginal bone loss in edentulous implant patients. *The International Journal of Oral & Maxillofacial Implants*, *11*(5), 620–625.

Jockusch, J., & Ozcan, M. (2020). Additive manufacturing of dental polymers: An overview on processes, materials and applications. *Dental Materials Journal*, *39*(3), 345–354. https://doi.org/10.4012/dmj.2019-123

Joda, T., & Bragger, U. (2016). Time-efficiency analysis of the treatment with monolithic implant crowns in a digital workflow: a randomized controlled trial. *Clinical Oral Implants Research*, *27*(11), 1401–1406. https://doi.org/10.1111/clr.12753


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Joda, T., Gintaute, A., Bragger, U., Ferrari, M., Weber, K., & Zitzmann, N. U. (2021). Time-efficiency and cost-analysis comparing three digital workflows for treatment with monolithic zirconia implant fixed dental prostheses: A double-blinded RCT. *Journal of Dentistry*, *113*, 103779. https://doi.org/10.1016/j.jdent.2021.103779

Joda, T., Zarone, F., & Ferrari, M. (2017). The complete digital workflow in fixed prosthodontics: a systematic review. *BMC Oral Health*, *17*(1), 124. https://doi.org/10.1186/s12903-017-0415-0

Jung, R. E., Schneider, D., Ganeles, J., Wismeijer, D., Zwahlen, M., Hammerle, C. H., & Tahmaseb, A. (2009). Computer technology applications in surgical implant dentistry: a systematic review. *International Journal of Oral and Maxillofacial Implants*, *24*(Suppl), 92–109.

Kim, J., & Lee, D. H. (2020). Influence of the postcuring process on dimensional accuracy and seating of 3D-printed polymeric fixed prostheses. *BioMed Research International*, *2020*, 2150182. https://doi.org/10.1155/2020/2150182

Kim, M. J., Choi, Y. J., Kim, S. K., Heo, S. J., & Koak, J. Y. (2017). Marginal accuracy and internal fit of 3-D printing laser-sintered Co-Cr alloy copings. *Materials*, *10*(1), 93. https://doi.org/10.3390/ma10010093

Komissarenko, D. A., Sokolov, P. S., Evstigneeva, A. D., Shmeleva, I. A., & Dosovitsky, A. E. (2018). Rheological and curing behavior of acrylate-based suspensions for the DLP 3D printing of complex zirconia parts. *Materials*, *11*(12), 2350. https://doi.org/10.3390/ma11122350

Kunavisarut, C., Jarangkul, W., Pornprasertsuk-Damrongsri, S., & Joda, T. (2022). Patient-reported outcome measures (PROMs) comparing digital and conventional workflows for treatment with posterior single-unit implant restorations: A randomized controlled trial. *Journal of Dentistry*, *117*, 103875. https://doi.org/10.1016/j.jdent.2021.103875

Martin-Ortega, N., Sallorenzo, A., Casajus, J., Cervera, A., Revilla-Leon, M., & Gomez-Polo, M. (2022). Fracture resistance of additive manufactured and milled implant-supported interim crowns. *The Journal of Prosthetic Dentistry*, *127*(2), 267–274. https://doi.org/10.1016/j.prosdent.2020.11.017

Methani, M. M., Revilla-Leon, M., & Zandinejad, A. (2020). The potential of additive manufacturing technologies and their processing parameters for the fabrication of all-ceramic crowns: A review. *Journal of Esthetic and Restorative Dentistry*, *32*(2), 182–192. https://doi.org/10.1111/jerd.12535

Mormann, W. H., Brandestini, M., Lutz, F., Barbakow, F., & Gotsch, T. (1990). CAD-CAM ceramic inlays and onlays: a case report after 3 years in place. *Journal of the American Dental Association (1939)*, *120*(5), 517–520. https://doi.org/10.14219/jada.archive.1990.0086

Muhlemann, S., Hjerppe, J., Hammerle, C. H. F., & Thoma, D. S. (2021). Production time, effectiveness and costs of additive and subtractive computer-aided manufacturing (CAM) of implant prostheses: A systematic review. *Clinical Oral Implants Research*, *32*(Suppl 21), 289–302. https://doi.org/10.1111/clr.13801

Muhlemann, S., Kraus, R. D., Hammerle, C. H. F., & Thoma, D. S. (2018). Is the use of digital technologies for the fabrication of implant-supported reconstructions more efficient and/or more effective than conventional techniques: A systematic review. *Clinical Oral Implants Research*, *29*(Suppl 18), 184–195. https://doi.org/10.1111/clr.13300

Muhlemann, S., Lakha, T., Jung, R. E., Hammerle, C. H. F., & Benic, G. I. (2020). Prosthetic outcomes and clinical performance of CAD-CAM monolithic zirconia versus porcelain-fused-to-metal implant crowns in the molar region: 1-year results of a RCT. *Clinical Oral Implants Research*, *31*(9), 856–864. https://doi.org/10.1111/clr.13631

Muhlemann, S., Lamperti, S. T., Stucki, L., Hammerle, C. H. F., & Thoma, D. S. (2022). Time efficiency and efficacy of a centralized computer-aided-design/computer-aided-manufacturing workflow for implant crown fabrication: A prospective controlled clinical study. *Journal of Dentistry*, *127*, 104332. https://doi.org/10.1016/j.jdent.2022.104332

No-Cortes, J., Ayres, A. P., Lima, J. F., Markarian, R. A., Attard, N. J., & Cortes, A. R. G. (2022). Trueness, 3D deviation, time and cost comparisons between milled and 3D-printed resin single crowns. *The European Journal of Prosthodontics and Restorative Dentistry*, *30*(2), 107–112. https://doi.org/10.1922/EJPRD_2306No-Cortes06

Obermeier, M., Ristow, O., Erdelt, K., & Beuer, F. (2018). Mechanical performance of cement- and screw-retained all-ceramic single crowns on dental implants. *Clinical Oral Investigations*, *22*(2), 981–991. https://doi.org/10.1007/s00784-017-2178-z

Osman, R. B., Alharbi, N., & Wismeijer, D. (2017). Build angle: Does it influence the accuracy of 3D-printed dental restorations using digital light-processing technology? *The International Journal of Prosthodontics*, *30*(2), 182–188. https://doi.org/10.11607/ijp.5117

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

Pan, S., Guo, D., Zhou, Y., Jung, R. E., Hammerle, C. H. F., & Muhlemann, S. (2019). Time efficiency and quality of outcomes in a model-free digital workflow using digital impression immediately after implant placement: A double-blind self-controlled clinical trial. *Clinical Oral Implants Research*, *30*(7), 617–626. https://doi.org/10.1111/clr.13447

Park, J. Y., Jeong, I. D., Lee, J. J., Bae, S. Y., Kim, J. H., & Kim, W. C. (2016). In vitro assessment of the marginal and internal fits of interim implant restorations fabricated with different methods. *The Journal of Prosthetic Dentistry*, *116*(4), 536–542. https://doi.org/10.1016/j.prosdent.2016.03.012

Park, S.-M., Park, J.-M., Kim, S.-K., Heo, S.-J., & Koak, J.-Y. (2019). Comparison of flexural strength of three-dimensional printed three-unit provisional fixed dental prostheses according to build directions. *Journal of Korean Dental Science*, *12*(1), 13–19. https://doi.org/10.5856/JKDS.2019.12.1.13

Pitta, J., Hjerppe, J., Burkhardt, F., Fehmer, V., Mojon, P., & Sailer, I. (2021). Mechanical stability and technical outcomes of monolithic CAD/CAM fabricated abutment-crowns supported by titanium bases: An in vitro study. *Clinical Oral Implants Research*, *32*(2), 222–232. https://doi.org/10.1111/clr.13693

Presotto, A. G. C., Barao, V. A. R., Bhering, C. L. B., & Mesquita, M. F. (2019). Dimensional precision of implant-supported frameworks fabricated by 3D printing. *The Journal of Prosthetic Dentistry*, *122*(1), 38–45. https://doi.org/10.1016/j.prosdent.2019.01.019

Pyo, S. W., Kim, D. J., Han, J. S., & Yeo, I. L. (2020). Ceramic materials and technologies applied to digital works in implant-supported restorative dentistry. *Materials*, *13*(8), 1964. https://doi.org/10.3390/ma13081964

Revilla-Leon, M., Besne-Torre, A., Sanchez-Rubio, J. L., Fabrega, J. J., & Ozcan, M. (2019). Digital tools and 3D printing technologies integrated into the workflow of restorative treatment: A clinical report. *The Journal of Prosthetic Dentistry*, *121*(1), 3–8. https://doi.org/10.1016/j.prosdent.2018.02.020

Revilla-Leon, M., Methani, M. M., Morton, D., & Zandinejad, A. (2020). Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns. *The Journal of Prosthetic Dentistry*, *124*(6), 730–737. https://doi.org/10.1016/j.prosdent.2019.09.018

Revilla-Leon, M., Meyer, M. J., & Ozcan, M. (2019). Metal additive manufacturing technologies: literature review of current status and prosthodontic applications. *International Journal of Computerized Dentistry*, *22*(1), 55–67.

16000501, 2023, S26, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/clr.14085 by Schweizerische Akademie Der, Wiley Online Library on [14/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Revilla-Leon, M., Meyer, M. J., Zandinejad, A., & Ozcan, M. (2020). Additive manufacturing technologies for processing zirconia in dental applications. *International Journal of Computerized Dentistry*, *23*(1), 27–37.

Revilla-Leon, M., & Ozcan, M. (2019). Additive manufacturing technologies used for processing polymers: current status and potential application in prosthetic dentistry. *Journal of Prosthodontics*, *28*(2), 146–158. https://doi.org/10.1111/jopr.12801

Revilla-Leon, M., Perez-Lopez, J., Barmak, A. B., Raigrodski, A. J., Rubenstein, J., & Galluci, G. O. (2022). Implant-abutment discrepancy before and after acrylic resin veneering of complete-arch titanium frameworks manufactured using milling and electron beam melting technologies. *Journal of Prosthodontics*, *31*(S1), 88–96. https://doi.org/10.1111/jopr.13422

Revilla-Leon, M., Sanchez-Rubio, J. L., Perez-Lopez, J., Rubenstein, J., & Ozcan, M. (2021). Discrepancy at the implant abutment-prosthesis interface of complete-arch cobalt-chromium implant frameworks fabricated by additive and subtractive technologies before and after ceramic veneering. *The Journal of Prosthetic Dentistry*, *125*(5), 795–803. https://doi.org/10.1016/j.prosdent.2020.03.018

Schneider, D., Sax, C., Sancho-Puchades, M., Hammerle, C. H. F., & Jung, R. E. (2021). Accuracy of computer-assisted, template-guided implant placement compared with conventional implant placement by hand-An in vitro study. *Clinical Oral Implants Research*, *32*(9), 1052–1060. https://doi.org/10.1111/clr.13799

Son, K., Lee, J. H., & Lee, K. B. (2021). Comparison of intaglio surface trueness of interim dental crowns fabricated with SLA 3D printing, DLP 3D printing, and milling technologies. *Healthcare*, *9*(8), 983. https://doi.org/10.3390/healthcare9080983

Stansbury, J. W., & Idacavage, M. J. (2016). 3D printing with polymers: Challenges among expanding options and opportunities. *Dental Materials*, *32*(1), 54–64. https://doi.org/10.1016/j.dental.2015.09.018

Sudbeck, S., Hoffmann, M., Reymus, M., Buser, R., Edelhoff, D., & Stawarczyk, B. (2022). Bending moment of implants restored with CAD/CAM polymer-based restoration materials with or without a titanium base before and after artificial aging. *Dental Materials*, *38*(9), e245–e255. https://doi.org/10.1016/j.dental.2022.06.009

Svanborg, P., Eliasson, A., & Stenport, V. (2018). Additively manufactured titanium and cobalt-chromium implant frameworks: Fit and effect of ceramic veneering. *The International Journal of Oral & Maxillofacial Implants*, *33*(3), 590–596. https://doi.org/10.11607/jomi.6028

Tian, Y., Chen, C., Xu, X., Wang, J., Hou, X., Li, K., Lu, X., Shi, H. Y., Lee, E.-S., & Jiang, H. B. (2021). A review of 3D printing in dentistry: Technologies, affecting factors, and applications. *Scanning*, *2021*, 9950131. https://doi.org/10.1155/2021/9950131

Wang, W., Yu, H., Liu, Y., Jiang, X., & Gao, B. (2019). Trueness analysis of zirconia crowns fabricated with 3-dimensional printing. *Journal of Prosthetic Dentistry*, *121*(2), 285–291. https://doi.org/10.1016/j.prosdent.2018.04.012

Williams, F. C., Hammer, D. A., Wentland, T. R., & Kim, R. Y. (2020). Immediate teeth in fibulas: Planning and digital workflow with point-of-care 3D printing. *Journal of Oral and Maxillofacial Surgery*, *78*(8), 1320–1327. https://doi.org/10.1016/j.joms.2020.04.006

Yildirim, B. (2020). Effect of porcelain firing and cementation on the marginal fit of implant-supported metal-ceramic restorations fabricated by additive or subtractive manufacturing methods. *The Journal of Prosthetic Dentistry*, *124*(4), 476 e471–476 e476. https://doi.org/10.1016/j.prosdent.2020.03.014

Zandinejad, A., Methani, M. M., Schneiderman, E. D., Revilla-Leon, M., & Bds, D. M. (2019). Fracture resistance of additively manufactured zirconia crowns when cemented to implant supported zirconia abutments: An in vitro study. *Journal of Prosthodontics*, *28*(8), 893–897. https://doi.org/10.1111/jopr.13103

**How to cite this article:** Ioannidis, A., Pala, K., Strauss, F. J., Hjerppe, J., Jung, R. E., & Joda, T. (2023). Additively and subtractively manufactured implant-supported fixed dental prostheses: A systematic review. *Clinical Oral Implants Research*, *34(Suppl. 26)*, 50–63. https://doi.org/10.1111/clr.14085

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