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*Systematic Review*

# Evaluation of Removable Partial Denture Metal Frameworks Produced by Digital Methods—A Systematic Review

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**Abstract:** (1) Introduction: This review aimed to synthesize the significant literature addressing digital techniques for producing removable partial denture (RPD) metal frameworks, focusing on oral fit outcomes. (2) Material and Methods: A systematic review of the Web of Science and Pubmed databases was performed according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines. The selection was for original articles in English containing relevant data on RPD metal frameworks produced with digital techniques, including study characteristics, digital techniques, and fit assessment methods and outcomes. (3) Results: From the 967 search studies, 405 were duplications, and 521 were excluded after screening against set criteria. A manual search included 21 studies resulting in 62 papers for review. Extra-oral was more frequently used than intra-oral scanning. The computer-assisted design was the most applied digital technique. Additive manufacturing was preferred to milling for direct and indirect fabrication of frameworks. Fit assessments were based on qualitative measures, but quantitative evaluation showed acceptable clinical fit for RPDs made by digital protocols. (4) Conclusions: The combination of direct metal additive manufacturing with conventional impression was the most used protocol and included better qualitative and quantitative fit outcomes than the other digital protocols.

**Keywords:** removable partial denture; framework production; digital; CAD-CAM; fit accuracy



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## 1. Introduction

The evolution of medical knowledge and technology has allowed people to live longer with fewer tooth losses, leading to an increasing need for partial oral rehabilitation [1]. Replacement of missing teeth and their attached structures is fundamental to restoring masticatory and phonetic functions, as well as aesthetics [2]. Despite the advantages of fixed prosthodontics, physiological, anatomical, and financial reasons make their application unfeasible [3]. Thus, removable partial dentures (RPDs) emerge as an alternative with a significant clinical impact, improving patients' quality of life [4].

The basic concepts of RPD framework design have been widely accepted for over 50 years [5]. Traditionally, the metal frameworks are produced by the lost-wax casting technique, which involves a series of demanding technical procedures even for experienced dental laboratory technicians [6,7]. This conventional protocol initiates with a clinical impression, followed by laboratory steps, including diagnostic cast production and surveying, refractory cast acquisition, waxing, casting, metal framework fabrication, and finishing [8]. Cobalt–chromium is usually the metal alloy used due to its good biocompatibility, appropriate wear and corrosion resistance, high fatigue strength, and low cost [7,9–12]. Titanium can also be used, but, despite the advantages of lower weight and lower modulus of elasticity, it has the disadvantage of lower yield strength [13–15]. Due to the complexity of conventional RPD production, many possible sources of errors may compromise the framework's strength, and functionality, and patient comfort [8,16,17]. Among various studies that assessed production errors, Rudd and colleagues reviewed and categorized a total of 243 errors [18–20].

A correct fit to the oral cavity is crucial for the success of the rehabilitation treatment [21]. However, in previous studies, the conventional lost-wax technique generated poor fit in a third of the metal frameworks produced, and almost half of them with gaps of up to 500 µm between the framework clasps and the abutment teeth [18,21–23].

Since the 1970s, digital techniques have been used in various areas of biomedicine, with significant advantages such as reduced labor cost and time, more predictable and reproducible results, and the potential to increase structural accuracy in human tissues [24–28]. To overcome the limitations of conventional RPD production, researchers began to apply not only computer-aided design (CAD) with RPD software but also computer-aided manufacturing (CAM) techniques and materials for the RPD metal framework production [4,29,30]. It is increasingly popular to adapt digital procedures for RPD metal framework production, combining digital and conventional techniques [31,32]. Nevertheless, digital techniques' contribution to RPD metal framework production needs to be clarified in the recent scientific literature. Also, robust evidence-based scientific knowledge of digitally produced metal frameworks' fit accuracy to the oral structures is scarce.

This article aimed to systematically review and organize the literature on the RPD metal framework production using digital techniques to ascertain the most frequently researched production protocols, characterize the methodologies of fit accuracy results, and systematize the evolution of the related research trends.

## 2. Materials and Methods

This systematic review assumed the orientations of the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) Statement [33,34]. The proposal for the study was registered at the National Institute for Health Research, International Prospective Register of Systematic Reviews (PROSPERO) platform with the number CRD42022354848 (File S1).

An electronic search for relevant publications until December 2022 was conducted in the Web of Science and PubMed/MEDLINE databases, using the keywords "Removable partial denture" and "Removable dental prosthesis". Each of these words was associated with the terms "digital OR CAD-CAM", "Intra-oral scanner OR Digital Impression", "computer design OR virtual design", "additive manufacturing OR rapid prototyping", "Mill*", "Resin Pattern OR Intermediate structure", "Selective laser sintering OR selective laser melting OR direct metal laser sintering OR electron beam melting", "Stereolithography OR fused deposition modeling OR digital light processing OR selective deposition modeling OR 3D printing OR 3D jet", and "fit OR accuracy".

Due to the scarce literature on RPD metal framework production with digital techniques, case reports, in vitro studies, and clinical studies were included in the search. A manual search of the references used in the included publications was performed to reveal additional relevant manuscripts.

Two reviewers (PC, CBN) independently screened citations and abstracts to detect articles that might fulfil the eligibility criteria. Full-text versions of these articles were then obtained and individually assessed by the same reviewers to ascertain their alignment with the criteria. Discussions involving a third reviewer (JP) resolved any disparities in judgments about study suitability. The same methodology was applied in the data collection process.

The publications included met the following criteria: (1) contained relevant data concerning the total production of RPD metal framework with at least one clasp; (2) applied at least one digital technique in the production of the RPD metal framework; and (3) were written in the English language. Studies were excluded if they (1) included partial dentures with a material other than metal; (2) were literature or systematic reviews and experts' opinions; (3) production of RPD combined with fixed prostheses; or (4) did not contain any relevant data on RPD production.

During the analysis of the complete manuscripts, information was collected in a data extraction form and organized according to the following features: study design, sample

size, and level of scientific evidence; techniques (and details such as equipment or software used) for information acquisition, analysis and design, intermediate structure production and metal framework fabrication; type of metal, and production protocol; and methods for fit assessment of RPD metal frameworks, fit qualitative outcome, fit assessment location, fit quantitative outcome, and comparison between production protocols.

Each study's scientific evidence level was classified using the Levels of Evidence Table defined by the Oxford Center for Evidence-based Medicine [35]. Category 1 included systematic reviews of randomized trials. Clinical trials, randomized, and non-randomized clinical studies were grouped in category 2. Category 3 assembled cohort studies. Case-control studies, case series, and case reports comprise category 4. Finally, category 5 incorporated mechanism-based reasoning. The production protocols used in each study were indicated through a classification created by the authors (Figure 1). Eleven categories were constructed according to the different combinations of digital and conventional techniques used in the four steps of the metal framework production ("information acquisition", "analysis and design", "intermediate structure production", and "metal framework fabrication"). Protocol 1 shows the total conventional workflow; Protocol 2 includes a conventional production using a physical cast digitally created; Protocols 3 and 4 use a conventional production with CAD analysis and indirect milling or additive manufacturing, respectively; Protocols 5 and 6 use conventional impression followed by CAD analysis and direct milling or additive manufacturing, respectively; Protocol 7 uses a conventional production using intra-oral scanning and a physical cast digitally created; Protocols 8 and 9 include casting of a digitally produced intermediate structure with indirect milling and additive manufacturing, respectively; Protocol 10 and 11 show the total digital workflow with direct milling or additive manufacturing, respectively.

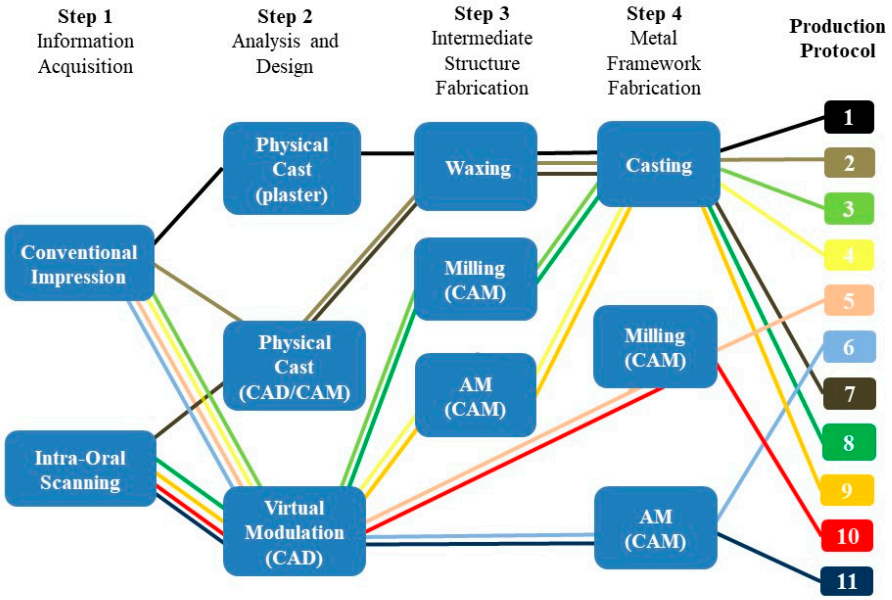


**Figure 1.** Diagram of the protocols to produce an RPD metal framework (Legend: CAD, computer-aided design; CAM, Computer-aided manufacture; AM, additive manufacturing).

Details of the evaluation of fit accuracy assessment were registered. If a qualitative method was used, the fit accuracy outcome was defined as bad, good, or excellent. In the "Bad" category were included terms such as "imperfection" and "reduced stability". All the qualitative outcomes that were described as "good", "satisfactory", "well", "properly", "adequate", "accurate", "improved", and "similar to traditional" were grouped in the "Good" category. Finally, the "Excellent" category grouped the outcomes that were described as "excellent" and "extremely". If a quantitative method was used, the location of the evaluation on RPD framework was recorded, as well as the gap thickness measurements between

the RPD metal frameworks and the oral supporting structures (in the clinical or laboratory environment), but also the discrepancies between the metal frameworks produced and the corresponding virtual design.

Additionally, the risk of bias in the clinical studies was assessed by the two independent reviewers, using the revised Cochrane risk-of-bias tool (ROBINS-I, Rob 2) and represented by the Risk-of-bias Visualization (robvis) tool.

## 3. Results

### *3.1. Search Results*

The total number of articles containing the search terms was 967. After the exclusion of 405 duplicate items, the number of recorded papers was 562. The search was conducted in two steps of screening: firstly, using the title and abstract papers (494 excluded) and afterwards their full-text papers (27 excluded). At the end, 41 manuscripts were eligible, to which 21 papers from a manual search were added, for a total of sixty-two selected studies for review (Figure 2).

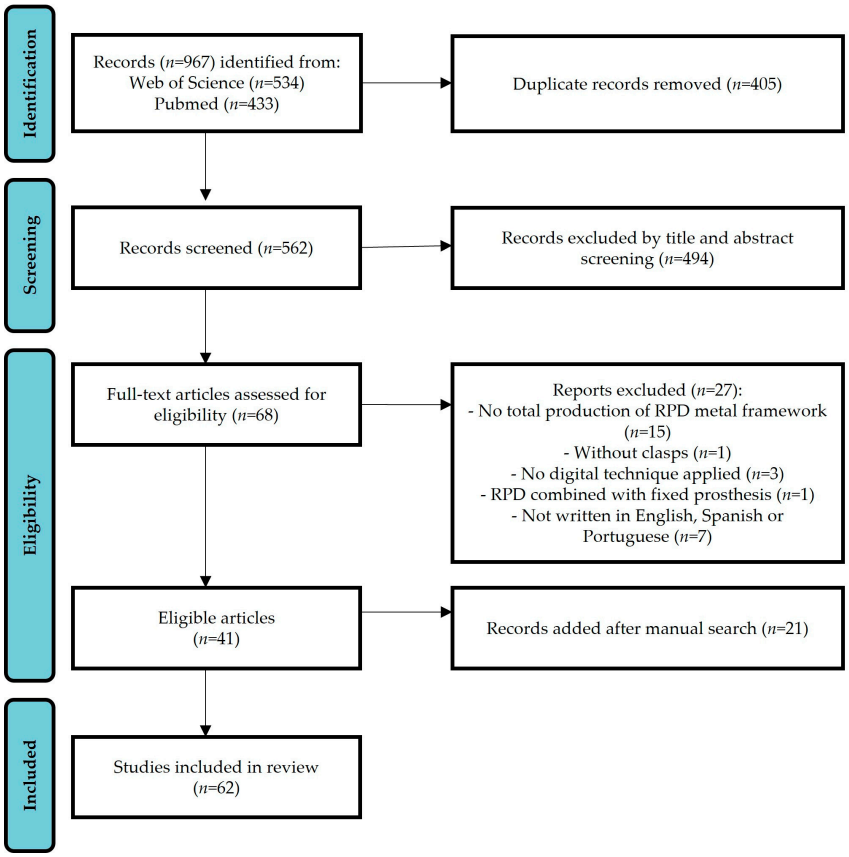


**Figure 2.** Flow chart of the procedures used for the article search.

### *3.2. Main Characteristics of the Studies*

The main characteristics of the included studies are listed in Table 1. Most of the included studies followed a low level of scientific evidence since they were based on case reports (thirty papers) and in vitro studies (nineteen papers). Of the thirteen controlled clinical studies, eight presented a reduced sample size (six to fifteen patients), and just one of these included studies showed randomization. From the clinical studies with sample size between twenty and twenty-nine patients, only three included a fit accuracy assessment of the RPD frameworks (Table 1).

**Table 1.** Information collected from the included studies.

| Study | Study Design | Sample Size | Level of Evidence | Information Acquisition (Equipment) | Analysis and Design (Software) | Intermediate Structure (Technique) | Framework Fabrication | Type of Metal (Brand) | Production Protocol |
|---|---|---|---|---|---|---|---|---|---|
| Williams, Bibb & Rafik, 2004 [36] | In vitro study | 2 | - | CImp+eOS (Comet 250) | CAD (Polyworks + Spyder + Matlab Surface Studio) | AM (SLA) | Casting | Co-Cr (Ndd) | 4 |
| Eggbeer, Bibb & Williams, 2005 [37] | In vitro study | 1 | - | CImp+eOS (Comet 250) | CAD (Polyworks + Spyder + FreeForm SensAble) | AM (SLA; JET) | Casting | Co-Cr (Nd) | 4 |
| Bibb et al., 2006 [19] | Case report | 1 | 4 | CImp+eOS (Comet 250) | CAD (Polyworks + Spyder + FreeForm SensAble) | AM (SLA) | Casting | Co-Cr (Nd) | 4 |
| Bibb & Eggbeer, 2006 [38] | Case report | 1 | 4 | CImp+eOS (Comet 250) | CAD (Polyworks + Spyder + FreeForm SensAble) | - | AM (SLM: Realizer 2) | Co-Cr (Nd) | 6 |
| Williams et al., 2006 [39] | Case report | 1 | 4 | CImp+eOS (Comet 250) | CAD (Polyworks + Spyder + FreeForm SensAble) | - | AM (SLM: Realizer 2) | Co-Cr (Nd) | 6 |
| Yan et al., 2009 [40] | Case report | 1 | 4 | CImp+eOS (Nd) | CAD (Nd) | AM (SLA) | Casting | Co-Cr (Nd) | 4 |
| Han, Wang & Lü, 2010 [41] | Case report | 2 | 4 | CImp+eOS (CXM-I) | CAD (Tang Long) | - | AM (SLM) | Nd | 6 |
| Chen et al., 2011 [42] | Case report | 2 | 4 | CImp+eOS (Not described) | CAD (Not described) | - | AM (SLM) | Ti (Nd) | 6 |
| Kreyer, 2012 [1] | Case report | 2 | 4 | CImp+eOS (3Shape D710) | CAD (3Shape DS) | AM (DLP; JET) | Casting | *N dd* | 4 |
| Wu et al., 2012 [43] | Case report | 1 | 4 | CImp+eOS (LSH600) | CAD (Geomagic Studio) | AM (SLA) | Casting | Co-Cr (Nd) | 4 |
| Kattadiyil et al., 2014 [44] | Case report | 1 | 4 | IntraS (Cadent iTero) | CAD (FreeForm SensAble) | AM (Nd) | Casting | Co-Cr (Nd) | 9 |
| Kim, Lee & Shin 2014 [45] | Case report | 1 | 4 | CImp+eOS (Nd) | CAD (FreeForm SensAble) | AM (Nd) | Casting | Nd | 4 |
| Lee & Lee, 2015 [46] | Case report | 1 | 4 | CImp+eOS (Nd | CAD (FreeForm SensAble) | AM (MJ) | Casting | Nd | 4 |
| Ahmed, Abbas & Omar, 2016 [47] | Clinical study | 6 | 2 | CImp+eOS (Nd) | CAD (3Shape DS) | - | AM (SLS: EOS M270 | Co-Cr (EOS SP2) | 6 |
| Arnold et al., 2018 [48] | In vitro study | 3 | - | CImp+eOS (3ShapeD900) | CAD (3Shape DS) | AM (Nd); MILL | Casting; AM (SLM: Concept Laser Mlab M1) | Co-Cr (Rema-nium Star CL) | 1, 3, 4, 6 |
| Mansour, Sanchez & Machado, 2016 [49] | Case report | 2 | 4 | IntraS (LAVA COS 3M) | Physical cast (Resin) | Waxing | Casting | Co-Cr (Nd) | 7 |

**Table 1.** *Cont.*

| Study | Study Design | Sample Size | Level of Evidence | Information Acquisition (Equipment) | Analysis and Design (Software) | Intermediate Structure (Technique) | Framework Fabrication | Type of Metal (Brand) | Production Protocol |
|---|---|---|---|---|---|---|---|---|---|
| Batisse et al., 2017 | Case report | 1 | 4 | IntraS (3Shape Trios) | CAD (3Shape DS) | - | AM (SLM: ProX DMP 200) | Co-Cr (Nd) | 11 |
| Hu, Pei& Wen, 2019 [50] | Case report | 1 | 4 | IntraS (3Shape Trios) | CAD (3Shape DS) | - | AM (SLM: EOS M280) | Ti (Nissin) | 11 |
| Lee et al., 2017 [51] | Clinical study | 10 | 2 | CImp+eOS (Activity 101) | CAD (FreeForm SensAble) | AM (MJ) | Casting | Nd | 4 |
| Wu, Li& Zhan, 2017 [52] | Case report | 1 | 4 | IntraS (CEREC Omnicam) | CAD (3Shape DS) | - | AM (SLM: BLT S200) | Ti (Nd) | 11 |
| Ye et al., 2017 [29] | Clinical study | 15 | 2 | CImp+eOS (3Shape D800) | CAD (3Shape DS) | - | AM (Nd: EOS M270) | Co-Cr (Wire-bond C+) | 1, 6 |
| Almufleh et al., 2018 [4] | Clinical study | 12 | 2 | CImp+eOS (Dental wings 3) | CAD (3Shape DS) | - | AM (SLS: Phenix PM100) | Co-Cr (Sint-Tech) | 1, 6 |
| Soltanzadeh et al., 2019 [53] | In vitro study | 10 | - | CImp+eOS (3Shape D900) | Physical cast (Resin), CAD (3Shape DS) | Waxing | Casting; AM (SLM: 3DRPD) | Co-Cr (Si-Tech ST2724G-A) | 1, 2, 6 |
| Husain et al., 2020 [8] | Case report | 1 | 4 | IntraS (3Shape Trios) | CAD (3Shape DS) | - | AM (SLM: EOS M270) | Co-Cr (Star-bond Easy) | 11 |
| Bajunaid et al., 2019 [54] | In vitro study | 15 | - | ExtraS (Zirkonzahn S600) | CAD (3Shape DS) | - | AM (SLM: Concept laser Mlab) | Co-Cr (Rema-nium CL) | 1, 6 |
| Chen et al., 2019 [55] | In vitro study | 3 | - | CImp+eOS (IScan D104i) | CAD (3Shape DS) | - | AM (SLM: Concept laser Mlab) | Co-Cr (Rema-nium CL) | 1, 6 |
| Mendes et al., 2019 [56] | Case report | 1 | 4 | IntraS (3Shape Trios) | CAD (3Shape DS) | - | AM (SLM: EOS—Phibo) | Co-Cr (Nd) | 11 |
| Tasaka et al., 2020 [57] | In vitro study | 5 | - | CImp+eOS (Smart Big) | CAD (Digistell) | AM (MJ) | Casting; AM (DMLS: EOS M270) | Co-Cr (Nd) | 4, 6 |
| Tregerman et al., 2019 [30] | Clinical study (R) | 9 | 2 | CImp+eOS (3Shape D800) + IntraS (3Shape Trios) | CAD (3Shape DS) | - | AM (SLM) | Co-Cr (EOS SP2) | 1, 6, 11 |
| Pereira et al., 2019 [58] | Case report | 1 | 4 | IntraS (3Shape Trios) | CAD (Dental Wings) | AM (SLA) | Casting | Co-Cr (Rema-nium GM 280) | 9 |
| Peng et al., 2020 [59] | In vitro study | 6 | - | ExtraS (3 Shape D900) | CAD (3 Shape DS) | AM (SLA) | Casting; AM (SLM: Concept Laser Mlab Cusing) | Co-Cr (Wironit; Rema-nium; Ti (Remati-tan) | 4, 6 |
| Wu et al., 2020 [60] | Case report | 1 | 4 | CImp+eOS (3Shape D850) | CAD (3Shape DS) | | AM (SLM: Concept Laser M2) | Ti (Ti6Al4V) | 6 |

**Table 1.** *Cont.*

| Study | Study Design | Sample Size | Level of Evidence | Information Acquisition (Equipment) | Analysis and Design (Software) | Intermediate Structure (Technique) | Framework Fabrication | Type of Metal (Brand) | Production Protocol |
|---|---|---|---|---|---|---|---|---|---|
| Tasaka et al., 2021 [61] | In vitro study | 5 | - | ExtraS (Smart Big) | CAD (Digistell) | AM (MJ) | Casting; AM (DMLS: EOSINT M270) | Co-Cr (EOS SP2) | 4, 6 |
| Rist & Cimic, 2016 [62] | Case report | 1 | 4 | CImp+eOS (Nd) | CAD (Nd) | | AM (SLM: Nd) | Nd | 6 |
| Lee et al., 2022 [63] | In vitro study | 5 | - | ExtraS (3Shape D900) | CAD (3Shape DS) | AM (SLA) | Casting; AM (SLM: ITRI AM System) | Co-Cr (Neoloy Denture) | 4, 6 |
| El-Khamisy et al., 2017 [64] | Clinical study | 6 | 2 | CImp+eOS (Shera eco-Scann7) | CAD (Nd) | - | MILL (Shera eco-mill 5x) | Co-Cr (Nd)) | 1, 5 |
| Malara et al., 2015 [65] | Case report | 1 | 4 | CImp+eOS (Nd) | CAD (Nd) | - | MILL (Nd) | Co-Cr (Nd) | 5 |
| Saad et al., 2019 [66] | Clinical study | 7 | 2 | CImp+eOS (3Shape D900) | CAD (3Shape DS) | AM (Nd) | Casting | Co-Cr (Nd) | 1, 4 |
| Carreiro et al., 2020 [67] | Case report | 2 | 4 | IntraS (3Shape Trios) | CAD (Dental Wings) | - | Casting | Co-Cr (Nd) | 9 |
| Hwang et al., 2021 [68] | In vitro study | 3 | - | ExtraS (3Shape E2) | CAD (Exocad Partial CAD) | - | AM (SLM: Dentium Metal Printer) | Ti (Nd) | 6 |
| Cabrita et al., 2021 [69] | Case report | 1 | 4 | CImp+eOS (3Shape D700) | CAD (3Shape DS) | - | AM (SLM: EOS Phibo) | Co-Cr (Nd) | 6 |
| Maryod & Taha, 2019 [70] | Clinical study | 20 | 2 | IntraS (3Shape Trios) | CAD (3Shape DS) | AM (DLP) | Casting | Co-Cr (Nd) | 1, 4 |
| Eldien, 2020 [71] | Clinical study | 10 | 2 | CImp+eOS (Ceramill map400) | CAD (Nd) | AM (Nd) | Casting | Co-Cr (Tico-nium Premium 100) | 4 |
| Kobayashi et al., 2021 [72] | In vitro study | 10 | - | ExtraS (Smart Big) | CAD (Digistell) | - | AM (SLM: EOSINT M270) | Co-Cr (EOS SP2) | 6 |
| Muheleman& Ozcan, 2022 [73] | In vitro study | 3 | - | ExtraS (Nd) | CAD (Siladent SilaPart) | MILL; AM (MJ) | Casting; AM (SLM: Concept Laser; DMLS:ProX DMP 100) | Co-Cr (Siladent V); Co-Cr (Dentau-rum Rema-nium star CL) | 1, 3, 4, 6 |
| Pugliese, Cataneo &Fortu-nato, 2021 [74] | Case report | 1 | 4 | CImp+eOS (Neway Open Tech 3D) | CAD (Nd) | - | AM (SLM: Nd) | Co-Cr (Nd) | 1, 6 |
| Snosi et al., 2021 [75] | In vitro study | 6 | - | ExtraS (3Shape D850) | CAD (3Shape DS) | MILL; AM (DLP) | Casting | Co-Cr (Bego Wirinium) | 3, 4 |
| Suzuki et al., 2022 [76] | Case report | 1 | 4 | IntraS (3Shape Trios) | CAD (Dental Wings) | - | AM (Nd: GE Concept Laser M2) | Ti (Ti-6Al-4V AP&C) | 11 |

**Table 1.** *Cont.*

| Study | Study Design | Sample Size | Level of Evidence | Information Acquisition (Equipment) | Analysis and Design (Software) | Intermediate Structure (Technique) | Framework Fabrication | Type of Metal (Brand) | Production Protocol |
|---|---|---|---|---|---|---|---|---|---|
| Ali et al., 2022 [77] | Clinical study | 25 | 2 | CImp+eOS | CAD (Nd) | - | Casting; AM (SLS: Nd) | Co-Cr (Nd) | 1, 6 |
| Oh, Jeon & Kim 2022 [78] | In vitro study | 10 | - | ExtraS (Medit Co. T500) | CAD (3Shape DS) | AM (DLP) | Casting; AM (Nd:Concept Laser Cusing 200R) | Co-Cr (Degudent Biosil F, Dentaurum Remanium star CL | 1, 4, 6 |
| Zhang et al., 2021 [79] | Case report | 2 | 4 | ExtraS (3Shape D2000) | CAD (Exocad Partial CAD) | - | AM (Nd) | Co-Cr (Nobilium Nobil Star Ultra) | 6 |
| Conceição et al., 2021 [80] | Clinical Study | 20 | 2 | ExtraS (Zirkonzahn S600 Arti) | CAD (Zirkonzahn Partial Planner) | - | AM (DMLS: EOSINT M270) | Co-Cr (EOS SP2) | 6 |
| Maraka et al., 2021 [81] | In vitro study | 5 | - | CImp+eOS (CS Ultra Pro) | CAD (Exocad Partial CAD) | - | AM (SLM: Sisma Mysint) | Co-Cr (Scheftner) | 1, 6 |
| Piao et al., 2022 [82] | Case report | 1 | 4 | CImp+eOS (Medit T500) | CAD (Exocad Partial CAD) | MILL | Casting | Nd | 3 |
| Alabdullah et al., 2022 [83] | In vitro study | 12 | - | CImp+eOS (Dentisply Sirona inEos X5) | CAD (3Shape DS) | - | AM (SLM: 3DRPD Co Lab) | Co-Cr (Nd) | 6 |
| Chia et al., 2022 [84] | Clinical Study (R) | 29 | 2 | CImp+eOS (3Shape D800) | CAD (3Shape DS) | - | AM (SLM: EOS M270) | Co-Cr (EOS SP2) | 1, 6 |
| Lee & Chen, 2022 [82] | Case report | 1 | 4 | CImp+eOS (3Shape E4) | CAD (Exocad Partial CAD) | - | AM (SLM: Nd) | Ti (Ti-6Al-4V) | 6 |
| Rockshad et al., 2022 [85] | In vitro study | 9 | - | ExtraS (3Shape E4) | CAD (3Shape DS) | AM (DLP) | Casting | Co-Cr (Nd) | 1, 4 |
| Cameron, Evans & Robb, 2022 [86] | Case report | 1 | 4 | IntraS (3Shape Trios 4) | CAD (Nd) | - | AM (SLS: Renishaw AM 400) | Co-Cr (Nd) | 11 |
| Pelletier, Pelletier & Dika, 2022 [87] | Clinical Study (R) | 24 | 2 | CImp+eOS (Nd) | CAD (Nd) | - | AM (SLS: 3DRPD Co Lab) | Nd | 1, 6 |
| Oh, Jeon & Kim, 2021 [88] | Case report | 1 | 4 | CImp+eOS (Nd) | CAD (3Shape DS) | - | AM (Nd: ChamplionM2150X) | Nd | 6 |
| Hamed, Hebeshi & Husseiny 2022 [89] | In vitro study | 10 | - | CImp+eOS (CAD Star CS.NEO) | CAD (Exocad Partial CAD) | AM (DLP) | Casting; AM (SLS: Vulcan Tech VM120) | Co-Cr (Sheftner Starbondeasy Pulver 30) | 4, 6 |

R, Randomized; Nd, Not described in the manuscript; Cimp+eOS, Conventional impression followed by digitization with extra-oral scanner; ExtraS, Extra-oral scanning; IntraS, Intra-oral scanning; AM, Additive manufacturing; MILL, Milling; SLA, Stereolithography; DLP, Digital light processing; MJ, Material jetting; SLS, Selective laser sintering; SLM, Selective laser melting; DMLS, Direct metal laser sintering.

The information acquisition was mainly performed using conventional impressions (thirty-nine papers) followed by the digitization of the master stone cast by an extra-oral scanning procedure using extra-oral or intra-oral scanners. In ten in vitro studies, the information of simulation models of dental arches was directly obtained by extra-oral scanning without any impression. In turn, intra-oral scanning was performed in thirteen included papers. The 3Shape equipment was the most requested for both extra-oral (sixteen papers) and intra-oral (ten papers) scanning (Table 1).

Digital techniques were executed to analyze the information and design the framework in almost all the included papers (sixty-one papers), highlighting the use of the 3Shape Dental System software (twenty-five papers). Conversely, the conventional technique using a physical cast was applied in just two papers (Table 1).

The additive manufacturing technique was used in the twenty-six studies that used the digital production of an intermediate structure made of a burnable material (resin with nineteen reports and wax with three reports), except for one study that used a milling technique. Stereolithography (SLA) was the additive manufacturing technique most described (nine studies), but material jetting technology (MJ) and digital light processing (DLP) were used in eight reports each. In turn, the milling technology was reported in four reports. Two studies achieved the intermediate structure using a conventional waxing technique (Table 1).

Considering the fabrication of the RPD metal framework, digital techniques were preferred in the included papers (forty-three papers) over conventional casting (twenty-nine papers). The additive manufacture (forty-two papers) was preferred using the selective laser melting (SLM) technique (twenty-seven papers), and the EOS equipment was the most described (eleven papers), specifically the EOSINT M270 (eight papers). In turn, the milling technique was applied in two studies (Table 1).

Regarding the metal used in the digital fabrication techniques, there was a clear preference for Co–Cr (thirty-two papers) over titanium (eight papers). The most used Co–Cr alloys for digital additive manufacture were EOS SP2 and Dentaurum Remanium Star CL (six papers each).

All protocols used to produce RPD metal frameworks with at least one digital step were described in the included papers, except for protocols 8 and 10, involving direct milling of the framework. The protocols based on the application of additive manufacturing techniques to create the intermediate structure to undergo casting (as protocols 4 and 9) or to directly fabricate the metal framework (as protocols 6 and 11) were the most studied (fifty-eight papers) (Table 1). Protocol 4 was the first to be described [36]), and since then, it has had more than triple the reports of protocol 11 (twenty-two vs. eight papers). However, protocol 6, which uses conventional impression followed by CAD analysis and additive manufacturing, is the most reported, in thirty-four papers (Table 1).

### 3.3. Fit Assessment Outcomes

The characteristics of the fit assessment used in the included studies are listed in Table 2. Most of the sixty-two included studies applied one assessment method (thirty-nine papers), and few performed two (eight papers) or three (three papers) methods. In addition, general evaluations (twenty-two papers) of the RPD framework fit were more common than entire framework (thirteen papers) or localized evaluations (twenty-one papers). The type of information collected was most frequently qualitative (twenty-six papers), but quantitative (twenty papers) or both (five papers) types were also used (Table 2).

**Table 2.** Fit accuracy assessment data collected from included studies.

| Study | Fit Assessment Method (Technique) | Fit Qualitative Constructed Outcome (Outcome Used) | Fit Assessment Location | Fit Quantitative Outcome (Thickness µm) | Protocols Studied and Fit Results |
|---|---|---|---|---|---|
| Williams, Bibb & Rafik, 2004 [36] | Ql (Visual inspection) | Nd | - | - | PT4 |
| Eggbeer, Bibb & Williams, 2005 [37] | Ql (Visual inspection) | Good (Satisfactory) | - | - | PT4 |
| Bibb et al., 2006 [19] | Ql (Visual inspection) | Good (Good) | - | - | PT4 |
| Bibb & Eggbeer, 2006 [38] | Ql (Visual inspection) | Excellent (Excellent) | - | - | PT6 |
| Williams et al., 2006 [39] | Ql (Nd) | Good (Good) | - | - | PT6 |
| Yan et al., 2009 [40] | Ql (Visual inspection) | Good (Good) | - | - | PT4 |
| Han, Wang & Lü, 2010 [41] | Nd | - | - | - | - |
| Chen et al., 2011 [42] | Ql+QT (Superimposition of entire framework to STL, analysis by CAE) | Good (Well) | EF | PT6 (+/− 172 µm) | PT6 |
| Kreyer, 2012 [1] | Nd | - | - | - | - |
| Wu et al., 2012 [43] | Ql (Visual inspection) | Good (Satisfactory) | - | - | PT4 |
| Kattadiyil et al., 2014 [44] | Ql (Visual inspection) | Excellent (Excellent) | - | - | PT9 |
| Kim, Lee & Shin 2014 [45] | Ql (Visual inspection) | Good (Good) | - | - | PT4 |
| Lee & Lee, 2015 [46] | Nd | - | - | - | - |
| Ahmed, Abbas & Omar, 2016 [47] | Ql (Citology, Tissue inflamation) | Good (Accurate) | - | - | PT6 |
| Arnold et al., 2018 [48] | Ql+QT (Visual inspection, Pressing test, Silicone specimen: Light microscope) | PT4 and PT6: Bad (imperfections and reduced stability) | OcR | PT3 (117 ± 34 µm) PT4 (323 ± 188 µm) PT6 (365 ± 205 µm) PT1 (133 ± 59 µm) | PT3 ≈ PT1 ≈ PT4 > PT6 |
| Mansour, Sanchez & Machado, 2016 [49] | Ql (Visual inspection; Pressing test) | Good (Properly) | - | - | PT7 |
| Batisse et al., 2017 [6] | Ql (Patient satisfaction) | Good (Good) | - | - | PT11 |
| Hu, Pei& Wen, 2019 [50] | Ql (Visual inspection; Patient satisfaction) | Good (Properly) | - | - | PT11 |
| Lee et al., 2017 [51] | QT (Silicone specimens: Stereo microscope) | - | EF, OcR, MC, OtC | EF (228 ± 173 µm) OcR (249 ± 135 µm) | PT4 |

**Table 2.** *Cont.*

| Study | Fit Assessment Method (Technique) | Fit Qualitative Constructed Outcome (Outcome Used) | Fit Assessment Location | Fit Quantitative Outcome (Thickness µm) | Protocols Studied and Fit Results |
|---|---|---|---|---|---|
| Wu, Li& Zhan, 2017 [52] | Nd | - | - | - | - |
| Ye et al., 2017 [29] | Ql+QT (Visual inspection; Pressing test; Stereo microscope) | PT6: Good (Well) | OcR | PT6 (174 ± 117 µm) PT1 (108 ± 84 µm) | PT1 > PT6 |
| Almufleh et al., 2018 [4] | Ql (Patient satisfaction) | - | - | . | PT6 > PT1 |
| Soltanzadeh et al., 2019 [53] | QT (Superimposition to STL design and to master cast; analysis by CAE) | - | EF | PT2 (5 ± 30 µm), PT6 (160 ± 20 µm) PT1 (27 ± 40 µm) | PT1 ≈ PT2 > PT6 |
| Husain et al., 2020 [8] | Ql (Visual inspection) | Good (Similar to PT1) | - | - | PT11 |
| Bajunaid et al., 2019 [54] | QT (Silicone specimens: Digital microscope) | - | OcR | PT6 (272.16 ± 173.55) PT1 (279.61 ± 175.21) | PT1 ≈ PT6 |
| Chen et al., 2019 [55] | QT (Silicone specimens: CAE Superimposition) | - | EF | PT6 (150–330 µm) PT1 (140–280 µm) | PT1 ≈ PT6 |
| Mendes et al., 2019 [56] | Ql (Superimposition to the STL design: Color difference map by CAE) | Good (Good) | - | - | PT11 |
| Tasaka et al., 2020 [57] | QT (Superimposition to STL design and to master cast: Color difference map by CAE) | - | EF, OcR, MC, OtC | PT6 (various individual results) | PT6 > PT4 |
| Tregerman et al., 2019 [30] | Ql (Visual Inspection) | - | - | - | PT11 > PT1 > PT6 |
| Pereira et al., 2019 [58] | Ql (Visual inspection, fit checker paste) | Good (Adequate) | - | - | PT9 |
| Peng et al., 2020 [59] | Ql+QT (Superimposition to STL design: Color difference map by CAE) | PT6: Good (Good); PT4: Nd | EF | PT4 (513 µm) PT6.CoCr (350 µm) PT6.Ti (344 µm) | PT6 > PT4 |
| Wu et al., 2020 [60] | Ql (Visual inspection, fit checker paste) | Good (Good) | | - | PT6 |

**Table 2.** *Cont.*

| Study | Fit Assessment Method (Technique) | Fit Qualitative Constructed Outcome (Outcome Used) | Fit Assessment Location | Fit Quantitative Outcome (Thickness µm) | Protocols Studied and Fit Results |
|---|---|---|---|---|---|
| Tasaka et al., 2021 [61] | QT (Superimposition to STL design: Color difference map by CAE) | - | EF, OcR, MC | PT6 (various individual results) | PT6 > PT4 |
| Rist & Cimic, 2016 [62] | Ql (Visual inspection; Patient satisfaction) | Good (Satisfactory) | - | - | PT6 |
| Lee et al., 2020 [63] | Nd | - | - | - | - |
| El-Khamisy et al., 2017 [64] | QT (Silicone specimens: Digital gauge, Contact, Visual score by CAE) | - | MC, OtC | PT5 (Guidding plates: 30 µm, MC:50 µm, Lingual bar: 70 µm); PT1 (Guidding plates: 140 µm, MC: 290 µm, Lingual bar: 530 µm | PT5 > PT1 |
| Malara et al., 2015 [65] | Nd | - | - | - | - |
| Saad et al., 2019 [66] | QT (Silicone and acrylic specimens: Caliper) | - | OcR, MC | PT4 (300 ± 40 µm) PT1 (390 ± 60 µm) | PT4 > PT1 |
| Carreiro et al., 2020 [67] | Ql (Visual inspection, fit checker paste) | Good (Good) | - | - | PT9 |
| Hwang et al., 2023 [68] | QT (Superimposition to the STL design; analysis by CAE softwares | - | EF | PT6 (124 ± 110 µm) | PT6 |
| Cabrita et al., 2021 [69] | Ql: Visual inspection | Good (Good) | - | - | PT6 |
| Maryod & Taha, 2019 [70] | Nd | - | - | - | ------ |
| Eldien, 2020 [71] | Ql: Visual inspection | Good (Improved) | - | - | PT4 |
| Kobayashi et al., 2021 [72] | QT (Superimposition to STL design) | - | EF, OcR, MC, OtC | PT6 (140 µm) | PT6 |
| Muheleman&Ozcan, 2022 [73] | QT (Silicone specimens: Digital microscope) | - | EF, OcR, MC, OtC | PT3 (206 µm), PT4 (211 µm), PT6 (249 µm), PT1 (286 µm) | PT3 ≈ PT4 ≈ PT6 > PT1 |

**Table 2.** *Cont.*

| Study | Fit Assessment Method (Technique) | Fit Qualitative Constructed Outcome (Outcome Used) | Fit Assessment Location | Fit Quantitative Outcome (Thickness µm) | Protocols Studied and Fit Results |
|---|---|---|---|---|---|
| Pugliese, Cataneo &Fortunato,2021 [74] | Ql (Visual inspection; Pressing test; Patient satisfaction) | Excellent (Extremely accuracy and satisfaction) | - | - | PT6 ≈ PT1 |
| Snosi et al., 2021 [75] | QT (Superimposition to STL desig,; analysis by CAE softwares) | - | EF, OcR | PT3 (EF: 150 ± 20 µm; OcR: 142 ± 22 µm), PT4 (EF: 179 ± 14 µm; OcR: 235 ± 22 µm) | PT3 > PT4 |
| Suzuki et al., 2022 [76] | QT (Silicone specimens: Profile projector) | - | MC | 200–500 µm | PT11 |
| Ali et al., 2022 [77] | Nd | - | - | - | - |
| Oh, Jeon & Kim 2022 [78] | QT (Silicone specimens: CAE by superimposition) | - | EF, OcR, MC | PT1 (EF: 280 ± 95 µm OcR: 240 ± 65 µm; MC 292 ± 110 µm), PT4 (EF: 332 ± 34 µm; OcR 260 ± 45 µm; MC 356 ± 34 µm), PT6 (EF: 241 ± 14 µm; OcR: 212 ± 17 µm; MC: 251 ± 16 µm) | PT1 ≈ PT4 ≈ PT6 |
| Zhang et al., 2021 [79] | Ql (Visual inspection; Patient satisfaction) | Good (Good) | - | - | PT6 |
| Conceição et al., 2021 [80] | QT (Silicone specimens: Micro-CT + DataViewer + CTAn) | - | OcR | PT1 (310 ± 113 µm), PT6 (333 ± 115 µm) | PT6 ≈ PT1 |
| Maraka et al., 2021 [81] | QT (Silicone specimens: Weight) | - | MC | PT1 (0.154 g), PT6 (0.215 g) | PT1 > PT6 |
| Piao et al., 2022 [82] | Nd | - | - | - | - |

**Table 2.** *Cont.*

| Study | Fit Assessment Method (Technique) | Fit Qualitative Constructed Outcome (Outcome Used) | Fit Assessment Location | Fit Quantitative Outcome (Thickness μm) | Protocols Studied and Fit Results |
|---|---|---|---|---|---|
| Alabdullah et al., 2022 [83] | QT (Silicone specimens: Digital Gauge, Superimposition) | - | OcR, MC, OtC | Silicone specimens OtC: 14 μm) (Superimposition OtC: 65 ± 24 μm; OcR: 82 ± 22 μm) | PT6 |
| Chia et al., 2022 [84] | Ql+QT (Visual inspection; Silicone specimens: Digital icroscope) | Good (Good) | OcR | PT1 (242 ± 45 μm) PT6 (274 ± 45 μm) | PT6 ≈ PT1 |
| Lee & Chen, 2022 [82] | Ql (Patient satisfaction) | Good (Satisfied) | - | - | - |
| Rockshad et al., 2022 [85] | QT (Superimposition) | - | OcR, MC, OtC | PT1 (103 ± 18 μm) PT4 (109 ± 21 μm) | PT4 ≈ PT1 |
| Cameron, Evans & Robb, 2022 [86] | Nd | - | - | - | - |
| Pelletier, Pelletier & Dika, 2022 [87] | QT (Silicone specimens: Scanning electron microscope) | - | OcR | PT1 (170 ± 92 μm) PT6 (390 ± 227 μm) | PT1 > PT6 |
| Oh, Jeon & Kim, 2021 [88] | Nd | - | - | - | - |
| Hamed, Hebeshi & Husseiny 2022 [89] | QT (Superimposition to STL: CAD analysis) | - | OcR, MC, OtC | PT4 (319 ± 8 μm) PT6 (160 ± 11 μm) | PT6 > PT4 |

PT: Protocol; Nd, Not described in the manuscript; Ql: Qualitative; QT: Quantitative; Micro-CT, Micro-computed tomography; EF, Entire framework; OcR: Occlusal rests; MC: Major connector; OtC: Other components; <, Worse than; ≈, Similar to; >, Better than.

Visual inspection of the gap between the metal framework and the oral support structures was the most frequently used qualitative method of fit assessment (twenty-three papers). Other qualitative methods described were the pressing test (four papers) and patient satisfaction (seven papers). Reverse techniques with computer-aided engineering (CAE) were also described as a qualitative method in three manuscripts. One study assessed the fit by the presence/absence of oral tissue inflammation; in another, the method was not described (Table 2).

Twenty-five studies measured the fit accuracy of the RPD frameworks by quantitative methods. The quantification of the gap between the metal frameworks and the supporting oral structures was done indirectly by the interposition of an impression material followed by thickness calculation (fourteen papers) or directly using the superimposition of the RPD framework and the master cast with CAE techniques (three papers) or after cutting the indirect structures (one paper). In nine studies, the authors evaluated the value of the discrepancy between the produced metal frameworks and the STL design, using superimposition CAE techniques. When the fit accuracy of RPD framework components was measured, the occlusal rest seats were the most mentioned location (seventeen papers), followed by the major connector (twelve papers) (Table 2).

Significant heterogeneity was observed in the fit accuracy quantitative assessment, even when the measured object was the same. The studies that applied the silicone interposition method (fourteen papers) differ in the thickness calculation technique. Analog measurement was done in seven studies, and a stereo microscope or a digital gauge was used in four. In studies that made a computerized measurement (eight papers), the evaluation was done using a digital camera (two papers) or microscope (two papers), a superimposition technique by CAE (two papers), a scanning electron microscope (one paper), and a micro-computed tomography equipment (one paper). Two of the eleven studies that used the digital superimposition method for quantitative evaluation applied a similar methodology using the color difference map CAE technique. The other nine differ in the CAE technique, equipment, data analysis software, or locations measured (Table 2).

When protocols were compared in qualitative assessments, protocol 6 (direct additive manufacturing using conventional impression) emerged with more Goods (eleven) and a high number of Excellents (two), except for one study that was considered Bad. Considering quantitative outcomes, protocol 6 was the most analyzed (nineteen papers), with discrepancy values between 14 and 365 µm. The lowest value of discrepancy presented was 5 µm, set by protocol 2 (conventional production using a physical cast digitally created), and the highest value was 513 µm, set by protocol 4 (conventional production with CAD analysis and indirect additive manufacturing) (Table 2).

The assessment methods presenting discrepancy values that were reported in more than one study were the following: the stereo microscope analysis of silicone specimens focusing on occlusal rest seats (two papers); the digital microscope evaluation of silicone specimens focusing occlusal rests (two papers); the digital superimposition of silicone specimens (two papers) and the digital superimposition of the entire framework to the STL design using a color difference map by CAE technique (two papers). In those studies, protocol 6 always presented better outcomes than protocol 4.

Two studies evaluated quantitatively, focusing on occlusal rests, by measuring silicone specimens using a micro-computed tomography technique or scanning electron microscope. Additionally, the other eight studies that evaluate the discrepancy of entire frameworks by digital superimposition to the STL design differ in the CAE technique (color difference map, distance measurement, or contrastive analysis), in the combination of scanner and software, or the framework locations evaluated.

Nineteen manuscripts compared protocols and used conventional protocol as a control, and eleven compared digital protocols. Twenty-two studies compared different production protocols and reported fit accuracy outcomes, fifteen by quantitative evaluation. Regarding the number of fit accuracy comparisons between protocols, protocol 6 (conventional impression followed by CAD analysis and direct additive manufacturing) was the most compared (twenty-five comparisons), followed by protocol 4 (indirect additive manufacturing; fifteen comparisons) and protocol 3 (indirect milling; seven comparisons).

### *3.4. Risk of Bias*

Considering the risk of bias of the eight non-randomized clinical studies that had full information, four presented a moderate risk, three presented a serious or even a critical risk, and only one presented a low risk of bias. (Figure 3). None of the randomized clinical trials presented a low risk of bias, and two showed a high risk of bias (Figure 4).

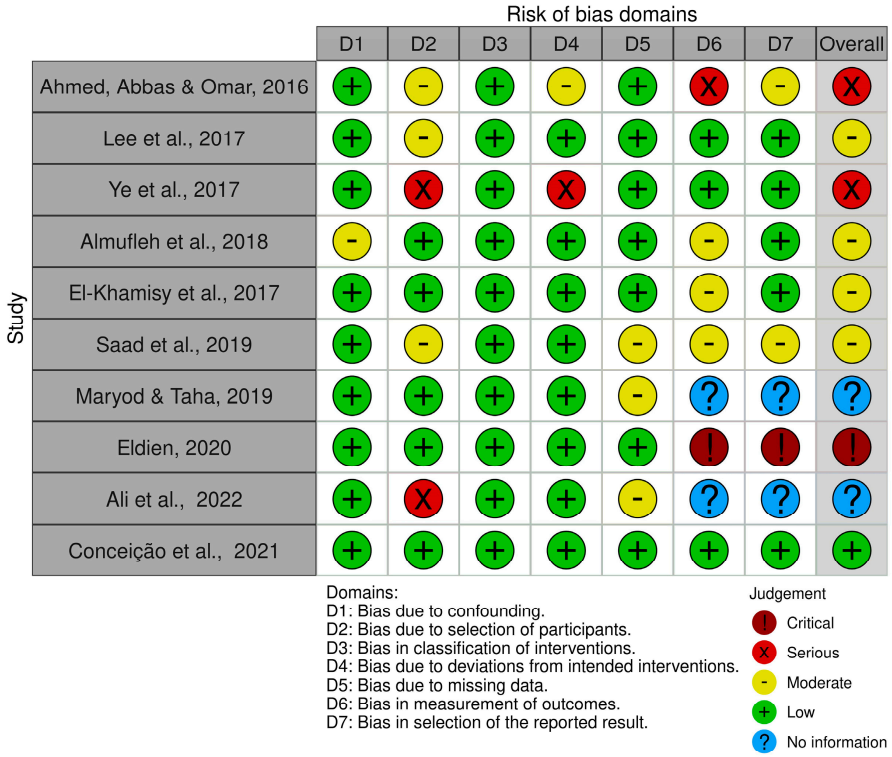


**Figure 3.** Risk of bias summary of the non-randomized clinical studies [4,29,47,51,64,66,70,71,77,80].

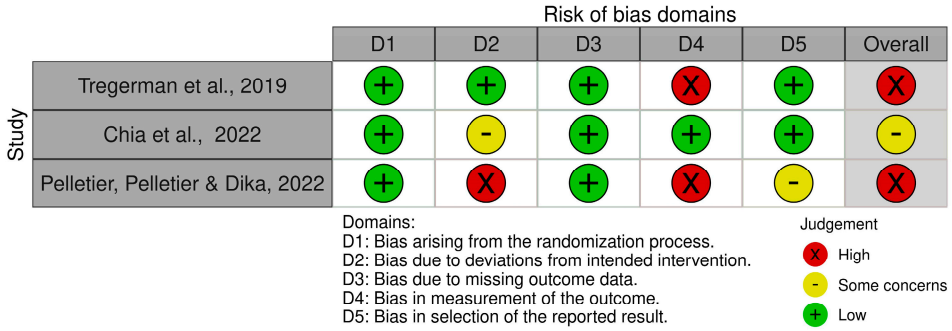


**Figure 4.** Risk of bias summary of the randomized clinical studies [30,84,87].

## 4. Discussion

The reviewed literature included only nine of the eleven possible protocols to produce RPD metal frameworks that combine digital and conventional techniques. The results show that all protocols are accurate, and protocols 4, 6, and 11 (total digital workflow) are the most frequently used in the reported articles. Digitally produced frameworks were clinically acceptable, but the fit accuracy outcomes were heterogeneous among studies since different assessment methods were used.

RPD frameworks are a highly personalized and complex structure, with a wide range of structural designs, created specifically for each patient. For this variation, there are additional difficulties in carrying out an investigation that quantitatively analyzes a standardized error that appears in the RPD production [19].

RPD framework accuracy assessment can be done by testing the fit in the plaster cast or in the patient [19,38]. From the sixty-two included papers, the most used assessment methods were qualitative, among which the visual inspection predominated. Quantitative assessment methods based on the distance between the RPD framework and support structures, measured directly or indirectly by using silicone, or based on the discrepancy of the produced metal framework to the STL design, are also described. The difficulties

of a quantitative general analysis of an RPD metal framework led analog fit accuracy evaluation to be mostly limited to occlusal rests, components that reflect the global fit of the RPD [29,55].

With the development of digital technologies, it is possible to use reverse CAE techniques which allow quantitative analysis not only by means of specific digital measurements but also by digital superimposition of the entire RPD framework, enabling better quality of production control [53]. However, the application of these techniques on a clinical daily basis is limited mainly by inaccurate soft tissue measurement with current intra-oral scanner technology and the patient exposure to X-ray radiation when a computerized tomography scan is used [31,55,90–92].

Compared to the early-1970s development of digital fixed prosthesis production, the first case of digital production of an RPD metal framework was only published in 2004. [36,93]. More than half of the studies included in the present work were published in the last four years, and among these, we found greater scientific evidence, which indicates the current late interest in digital RPD frameworks. Nevertheless, scientific evidence is still weak, as most are case reports (thirty papers) or in vitro studies (nineteen papers). From the thirteen clinical studies, eleven performed a fit accuracy evaluation, and the majority of these (eight papers) presented a reduced sample size ($\leq$15 patients). Also, it is important to consider that in the thirteen studies with higher scientific evidence level, only one presented low risk of bias and five presented high, serious, or even critical risk. Therefore, a first appreciation of this systematic review is the need for future research on this topic with a higher level of scientific evidence and lower risk of bias.

### *4.1. Production Protocols Used in the Studies*

Digitization of the information by scanning is always needed for the application of digital techniques. The studies that described the information acquisition by extra-oral scanning, without conventional impression, were in vitro studies that used simulation models of maxillary arches. As is well known, in a clinical approach, extra-oral scanning is always preceded by a conventional impression. Thus, the protocols presented in those papers were defined as if they started with a conventional impression.

The intra-oral scanning technique involves highly developed digital tools for clinical practice. However, the equipment technologies still have limitations on the trueness of entire arches and extensive edentulous edges related to the intra-oral environment and the camera position [92,94,95]. Moreover, a digital dynamic impression is still impossible digitally [44,51]. There are other methods for acquiring digital information, such as Cone Bean Computer Tomography (CB/CT) or Computer Tomography Scan (CT Scan), but these were not considered by the researchers due to inadequate patient exposure to irradiation [40,96,97].

The protocol with the most research (thirty-four papers) was protocol 6 (direct additive manufacturing using conventional impression). This protocol differs from protocol 11 (direct additive manufacturing using intra-oral scanning) by using conventional impressions to acquire information, and diverges from protocol 4 (indirect additive manufacturing using conventional impression) since it enables direct metal fabrication, making the fabrication of the intermediate structure unnecessary. The production of an intermediate structure, a crucial step in the conventional protocol, is an additional source of potential errors; hence, there is nowadays a preference for digital protocols that skip this step.

In the present study, the protocol applied by Bajunaid and colleagues [54] was defined as protocol 6, even though there was no conventional impression, as the scanning of the information of the simulation model was performed with an extra-oral scanner. In the study by Soltanzandeh and colleagues [53], the intraoral scanner was used to perform an extra-oral scanning of the simulation model. Hence, the protocols in question were considered as 2 (conventional impression and production using CAD analysis) and 6, not as 7 (conventional production using iOS and CAD analysis) and 11 (direct additive manufacturing using iOS), respectively.

After digitizing the information, the initial digital RPD framework designs implied the combination of several types of software. Currently, the analysis and design software already have all the tools combined, allowing integration of the digitized information, analysis of the path of insertion, and design of the RPD framework using libraries of components that can be customized. Nevertheless, the digital design software for RPD frameworks is still under development and improvement [4].

The protocols that involve milling to obtain an RPD metal framework are less investigated, since protocols 3 (indirect milling using conventional impression) and 5 (direct milling using conventional impression) were only described, in four and two studies, respectively. Protocols 8 (indirect milling) and 10 (direct milling), both using intra-oral scanning, are not mentioned in the included papers. Despite the possibility of a better finish than the additive technology, milling techniques are described as inappropriate for producing RPD metal frameworks because of the disadvantages of material waste and limitations in complex designs [28,36,48,57,96,98]. In the scientific literature, the production of RPD frameworks by milling techniques is related mostly to non-metallic materials such as polyether-ether-ketone (PEEK) [91,99–101].

The most reported digital technology for directly producing an RPD metal framework was selective laser melting (SLM), and the most described equipment was the EOSINT M270. These results could be controversial since this equipment is usually for structure production through direct metal laser sintering (DMLS) [61], revealing some confusion between these concepts. Those techniques differ in the energy beam and the chamber conditions, factors that determine the mode of union between the metal powder particles. In the SLM technique, there is a total fusion of the various particles of metal powder [96]. In turn, in the DMLS, there is a fusion of particles with a low melting point, while those with a higher melting point are partially fused at their periphery. [16,102,103]

### *4.2. Fit Assessment Evaluation*

Rehabilitation with RPD involves challenges in defining an accurate pathway for insertion and removal since minor errors in the rigid framework can lead to significant discrepancies in fit [30]. Nevertheless, in many of the included studies, the fit accuracy assessment was made through a qualitative evaluation, which usually fails in reproduction due to subjectivity and difficulty of standardization or criteria definition [48].

The fit accuracy assessment based on a quantitative evaluation was applied in less than half of the included papers (twenty-five papers). Different methods used for framework production and evaluation were applied, meaning it was impossible to compare outcomes between studies directly. Most of those studies were made in the laboratory, and most clinical studies had small sample sizes. In addition, three clinical studies used experimental procedures, as different master casts for each protocol evaluated, which may reduce the probability of accurate results and can introduce bias [29,84,87].

Some studies used standardized values for the meaning of the distance found between framework occlusal rests and dental rest seats. Considering the cumulative errors in the production steps, some authors defined a gap from 0 to 50 µm as close contact and a gap from 50 to 311 µm as acceptable [37,53].

Protocols 2 (conventional production using a physical cast digitally created) and 3 (conventional production with CAD analysis and indirect milling) emerged as those with the lowest quantitative discrepancy, and protocol 9 (casting of a digitally produced intermediate structure with additive manufacturing) was classified as "excellent" in qualitative analysis. However, protocols 2 and 3 were evaluated in fewer studies (one to three publications each), and protocol 9 was evaluated in three case reports with no control group and a low level of evidence. Moreover, the study that described protocol 2 used a methodology that presented impingement of the RPD frameworks on the master cast [53]. That situation can be explained by the fact that the authors did not use a reference image of the RPD framework inserted on the master cast for the superimposition protocol, thus not allowing an interpretation of the discrepancy gap values in absolute terms but in a relative way [53].

Of the remaining protocols, the one that stands out most was protocol 6 (direct additive manufacturing using conventional impression) because it was the most reported (thirty-four papers) and presented the highest number of Excellents (two) and Goods (eleven). Also, compared with protocol 4 (indirect additive manufacturing using conventional impression), it had better quantitative assessment results in four direct comparisons. Also, compared with protocol 11 (total digital flow with additive manufacturing), protocol 6 presented more Excellent or Good results (eleven against five).

Considering the studies comparing protocol 6 to the conventional control group (protocol 1), eight studies showed similar or better results than protocol 6; one of those was the only clinical study with low risk of bias. Taking into account the seven reports that showed the opposite, some considerations are essential to contemplate. Most laboratory studies did not perform finishing procedures to the AM frameworks (these naturally present a rougher surface, which disfavors their results), used different master casts for each production protocol, or applied evaluation methodologies that damaged the RPD frameworks before the measurements. For the clinical studies, a qualitative fit evaluation or a quantitative assessment was made using different master casts for each production protocol, which can quickly introduce bias. Two of those seven studies declared discrepancy values for AM protocol under 200 µm, a value that is like the discrepancy of the conventional protocol achieved by the studies conducted by Stern (173–215 µm) and by Dunhaim (193 ± 203 µm) [18,23]. Additionally, three clinical studies that presented the worst accuracy fit outcome of protocol 6 compared to the conventional group were classified with high or serious risk of bias. The differences in the framework designs, properties of the material, and production parameter definitions can also explain the divergence between the outcomes of the studies [68,96].

Considering the scientific level of evidence, risk of bias, fit accuracy outcomes, and the known disadvantages of intra-oral scanning and the milling technique, this review suggests that, to produce an RPD metal framework, protocol 6 (direct additive manufacturing using conventional impression) allows a combination of conventional and digital techniques that guarantees an excellent clinical result and is the best alternative to the conventional protocol [4,39,54,55,57,59,61,96].

Furthermore, the financial investment for the application of protocol 6 includes the extra-oral laboratory scanner and the CAD software since the created STL file can be easily sent to production centers. Currently, the production cost of RPD metal frameworks by protocol 6 is like the cost of the conventional protocol, with a tendency to be reduced in the future [8].

With two researchers to collect and analyze the data and one more to resolve any disparities in the final judgment, the time to conclude this review was longer than predicted. However, this method allowed minimizing bias.

Limitations of this systematic review need to be considered. Most included papers had low evidence levels, the clinical studies had low sample sizes, and just one of those presented low risk of bias. Moreover, it was impossible to perform a meta-analysis due to the significant heterogeneity of the methodologies and outcomes of the studies.

### *4.3. Future Approaches*

The intra-oral scanning technologies are becoming more accurate and more capable of digitizing soft tissues. Their introduction in the production protocol of RPD metal frameworks explores the advantages of the total digital workflow (defined as protocol 11 in this review), but also the potential to overcome the limitation of the soft tissues' information acquisition by conventional impressions, namely the floppy tissue depression and material distortions.

The finishing procedures of RPD metal frameworks use burs, rubbers, brushes, pastes, and electrolytic baths, with an average surface metal loss of 127 µm [104]. This value corresponds to almost 75% of the gap value identified in the fit accuracy assessment of the conventional protocol (protocol 1) [18,23]. To overcome this problem and complete the entire production cycle, some studies in the literature have already explored digital

finishing in clasps through milling after direct additive manufacturing [105,106], producing smoother surfaces and higher accuracy [14,27,106].

Co–Cr is still the preferred alloy for RPD metal frameworks due to the advantages of its mechanical properties and costs over Ti [10,27]. However, the disadvantage of esthetic concerns and corrosion led to increasing research in non-metallic materials, namely poly aryl-ether-ketone polymers (PAKP) [5] such as polyether-ether-ketone (PEEK) [48,91] and yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) [14,107].

Digital technology is a viable means to reduce cost, time, and production errors. Nevertheless, it is unanimous among the various researchers that future investigations will be essential to increase the scientific evidence and the quantitative fit accuracy assessment through clinical studies with larger sample sizes and lower risk of bias. Studies with controlled confounding variables are needed to assess the clinical fit accuracy of digital RPD frameworks in the long term. Other research will be fundamental to improve prosthetic design software (such as prediction of retention force according to tooth mobility) and to explore equipment, production parameters, and mechanical properties of the digital RPD metal frameworks. This way, in the future, it will become possible to produce RPD frameworks more quickly, with fewer human errors, less waste, higher reproducibility, and higher accuracy, improving the success of patients' oral rehabilitation.

## 5. Conclusions

Regarding the findings of this systematic review, the following conclusions were presented:

- Eleven protocols of different combinations of digital and conventional techniques to produce an RPD metal framework can be described;
- All studied protocols with digital techniques exhibit fit accuracy within the acceptable clinical range for RPDs;
- The protocol that combines direct metal additive manufacturing with the conventional impression (protocol 6) was the most frequently used in the literature and presented better qualitative and quantitative fit accuracy outcomes in comparison with the other digital protocols;
- Considering the number of studies and the fit accuracy outcomes, protocol 6 seems to be the best alternative to the conventional protocol, ensuring a good fit within a reasonable cost and time investment. However, more studies are needed to support these conclusions since the low scientific evidence quality and the significant heterogeneity of the methodologies applied in the included papers show that there is still much room for improvement.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app131910824/s1, File S1: PRISMA 2020 Checklist.

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