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Systematic Review

Three-Dimensional Accuracy of Surgical Guides for Static Computer-Aided Implant Surgery: A Systematic Review

Lucio Lo Russo [1,†], Mariani Pierluigi [2,*,†], Khrystyna Zhurakivska [1], Chiara Digregorio [1], Eleonora Lo Muzio [1,3] and Luigi Laino [2]

[1] Department of Clinical and Experimental Medicine, School of Dentistry, University of Foggia, 71122 Foggia, Italy; lucio.lorusso@unifg.it (L.L.R.); khrystyna.zhurakivska@unifg.it (K.Z.); chiaradigregoriogos@alice.it (C.D.); eleonora.lomuzio@edu.unife.it (E.L.M.)

[2] Multidisciplinary Department of Medical-Surgical and Odontostomatological Specialties, University of Campania, "Luigi Vanvitelli", 81100 Naples, Italy; luigi.laino@unicampania.it

[3] Department of Orthodontic, University of Ferrara, 44121 Ferrara, Italy

* Correspondence: marianipier@gmail.com; Tel.: +39-3273397381

† These authors contributed equally to this work.

Abstract: Background: The purpose of this study was to evaluate the dimensional accuracy of surgical guides for static computer-aided implant placements processed using milling or 3D printing. Methods: A comprehensive literature search was performed on electronic databases inclusive of PUBMED, SCOPUS, Cochrane Database of Systematic Reviews, EBSCO host Research Databases, and Web of Knowledge were searched without restriction to date. Studies investigating the surgical guides fabricated by milling or 3D-printing, comparing them with their computer-aided design model, and reporting outcome measures about the accuracy of the internal/external surface, the angular deviation of the sleeves, and the vertical or horizontal deviations of the sleeves' access were included. Results: From 1928 retrieved records, 33 studies were selected; 11 out of them fulfilled the eligibility criteria. All studies analyzed printed surgical guides, while only two studies analyzed both printed and milled templates. Studies were very heterogeneous in methodology and equipment; moreover, different parameters were used for accuracy measurements which made their results not comparable and quantitative synthesis not feasible. Conclusion: There is no clear evidence to address which manufacturing technology provides surgical guides with better accuracy, although milling might achieve better results, at least in terms of reduced variation. For additive technologies, several factors could influence accuracy. Since this issue has sensible clinical implications, future studies are encouraged.

Keywords: milling surgical guide; 3D printing surgical guide; computer-aided implant surgery; accuracy; trueness; precision; additive manufacturing technologies; subtractive manufacturing technologies

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1. Introduction

Advancements in digital imaging applied to dentistry, as well as progress in computer-aided design (CAD) software technologies, make possible virtual planning of implant treatments. This utilizes Cone-Beam Computed Tomography data merged with surface scan data to assess and define the optimal implant position for surgical safety [1] and favorable prosthetic support [2].

Two main approaches have been described to transfer the planned information at the surgical procedure and obtain the corresponding desired and planned implant position [2]: (i) a dynamic system, based on a navigation device using an optical tracking system which is capable of providing real-time information of the surgical instruments' position in relation to the patient's anatomy; (ii) a static system, which utilizes a surgical guide as a means to incorporate all information for the mechanical guiding of surgical instruments to obtain the planned implant position.

The static approach is more commonly used [3] and it has the potential to optimize implant position, increase predictability, or decrease surgical invasiveness [4]. Although it has been proven to provide a reasonable mean accuracy [5], it is not a flawless procedure, and the actual implants position (obtained after implant placement) may be quite different from the planned position.

Surgical guides have a main role in static computer-guided implant surgery, and they were designed in conjunction with the virtual planning and subsequently fabricated using CAD/computer-aided manufacturing (CAM) additive (printing) [6] or subtractive (milling) [7] technologies, whose intrinsic tolerance may sensibly affect the surgical guide dimensional accuracy [8].

The error of the guided implant surgery is it is the cumulative result of all possible inaccuracies along all stages of the guided implant placement procedure [9] which are cumulative and interactive, and include not only the surgical guides' dimensional inaccuracies, but all possible errors from data acquisition [10], management [11], and merging [12], to surgical guide stabilization [13] or bone features [14].

There are reviews in the literature evaluating the accuracy of computer-guided implant surgery by evaluating the accuracy of implant positioning which is represented by the quantity of linear and angular deviations occurring between the implant's planned position and the effective implant position [15,16]. However, there are no systematic reviews in the literature that evaluate the accuracy of the surgical guides comparing them with the virtual models (CAD) [17]. This is a fundamental prerequisite that contributes to the overall accuracy of computer-guided surgery.

The most relevant features of surgical guides affecting their contribution to the overall accuracy of computer-guided implant surgery are the accuracy of the fitting internal surface and the accuracy of the cylinder-shaped holes where the sleeves are inserted. The former is responsible for the adaptation to the supporting tissues and structures, and the latter can guarantee the congruence between the planned implant axis and the obtainable implant axis, as well as the correct position in the apico-coronal direction; both can be affected by the manufacturing process of the surgical guides.

There is no clear evidence as to which manufacturing process factors could improve/affect the accuracy of both the milled and printed surgical guides and which of these two processing techniques can provide better accuracy of surgical guides [18]. This has been seldom investigated [19–22]; nonetheless, it deserves special attention, especially in the scenario where the in-office production of surgical guides is becoming more and more common due to the increasing diffusion of both planning and manufacturing the digital technologies [17].

Therefore, the purpose of this study was to systematically review the published studies concerning the dimensional accuracy of surgical guides with the aim of investigating which factors of the manufacturing process, both printing and milling, can affect the accuracy of the guide for implant surgery and which of the two technologies (milling or printing) produces more accurate templates compared to their CAD model.

2. Materials and Methods

2.1. Protocol and Search Strategy

Ethics approval was not required for this systematic review. The review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement and the Patient or Population, Intervention, Control or Comparison, and Outcome (PICO) approach. The protocol was designed a priori and registered on the online database PROSPERO.

The formulated PICO questions were: When dealing with the fabrication of surgical guides for static computer-aided implant surgery, does the type of manufacturing technology (3D printing or milling) affect the surgical guides' accuracy?

An electronic search of the English language literature was performed up to January 2022 on the following databases: PUBMED, SCOPUS, Cochrane Database of Systematic Reviews, EBSCO host Research Databases, and Web of Knowledge. The research process was carried out via a combination of MeSH terms and free text words, combined using some Boolean operators (AND, OR). The following protocol was used: (“Dimensional Measurement Accuracy”[Mesh] OR accuracy OR trueness OR precision OR angulation OR deviation OR distance) AND (“Dental Implantation”[Mesh] OR “Dental Implants”[Mesh] OR “Surgery Computer-Assisted”[Mesh] OR “surgical guide*” OR “surgical template*” OR stent OR “dental implant*” OR “guided surgery” OR “guided implant placement” OR “implant surgery”)) AND (“Printing Three- Dimensional”[Mesh] OR “Computer-Aided Design”[Mesh] OR “mill*” OR “3D print*” OR “additive manufactur*” OR “subtractive manufactur*” OR “CAD-CAM”). In addition, a direct search was also performed in the bibliographies of all reviewed articles. No restrictions were applied about the year of publication.

2.2. Eligibility Criteria, Studies Selection, and Data Collection Process

Studies fulfilling the following eligibility criteria were considered eligible for inclusion in this review:

(a) published studies in the English language focused on the dimensional accuracy of surgical guides for static computer-aided implant placement;

(b) reporting outcomes measures about at least one of the following parameters related to the investigated surgical guides: trueness or precision of the internal and/or external surface, angular deviation of the sleeves, vertical or horizontal deviations of the sleeves’ access;

(c) the CAD model of the surgical guide was the reference for the measurement of the above outcomes;

Failing to meet such criteria caused the exclusion of the study.

Eligibility assessment was independently performed in a standardized manner by two reviewers (CD and PM). In the first round, the reviewers, by screening the titles and abstracts of the papers retrieved from the searched data sources, excluded studies that did not focus on the surgical guides’ dimensional accuracy. Thus, retained papers were read in full text in the second round. Any disagreement was resolved via discussion between the two reviewers. At the end of the second round of the selection process, papers fulfilling all the inclusion criteria were considered for data extraction. This process was performed independently by the reviewers via an ad hoc extraction sheet; the following data items were recorded for each included study: author names, year of publication, sample size, fabrication equipment and technologies, details of the processing procedure, equipment used for digitization of the manufactured surgical guides, software programs used for superimposition and measurements, parameter used to measure accuracy, and the data related to the outcomes of interest.

2.3. Risk of Bias Assessment

Reviewers independently evaluated the risk of bias in each included study by using an adaptation of the methods applied in a similar systematic review [23]. Descriptions of the following parameters were used to assess each article’s risk of bias: sample size calculation, details regarding 3D-printing (layer thickness, orientation of the surgical guide on the printing platform), details regarding milling process/strategy, blinding of the evaluation, measuring the accuracy at different portions (surface, sleeve) of the surgical guide, and the statistical analysis carried out. A “yes” was assigned where the parameter was reported in the text, and a “no” if the information was absent, incomplete, or unclear. The risk of bias was classified according to the sum of “yes” marks received as follows: 1 to 2 = high, 3 to 4 = medium, and 5 to 6 = low risk of bias.

3. Results

3.1. Studies Selection

The flowchart of the selection process is detailed in Figure 1. A total of 1928 records were retrieved from databases and screened by title and abstract. Of these, only 33 were considered eligible for the full-text examination. At the end of the full-text examination, only 11 papers [8,19,22–31] met the eligibility criteria and were included in the qualitative synthesis (Table 1).

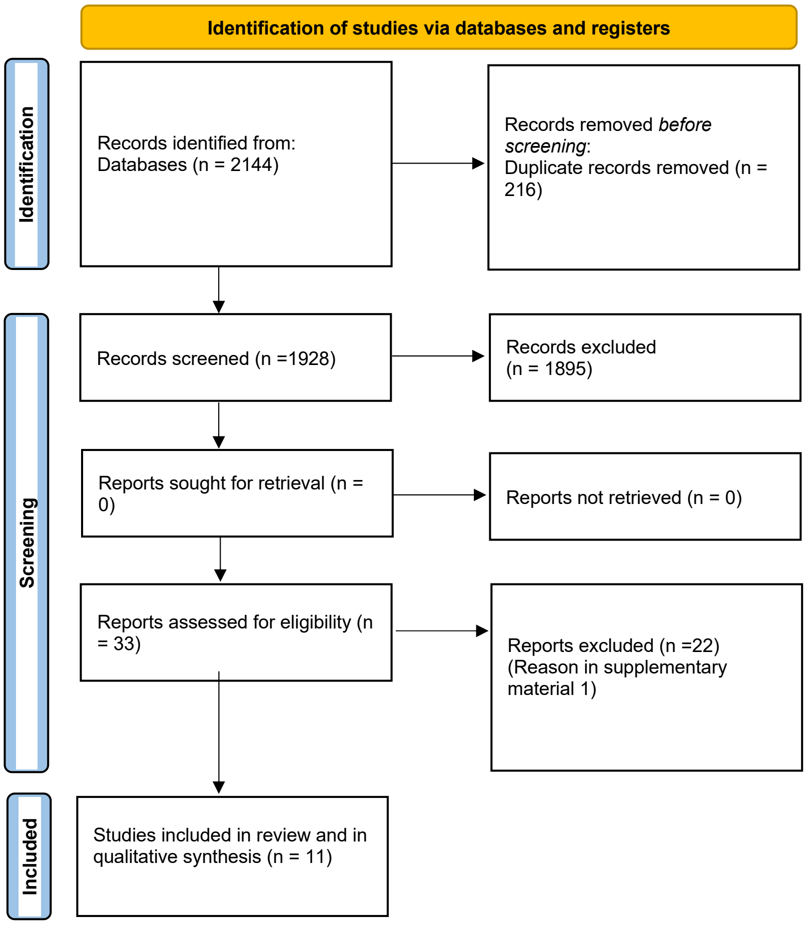

Figure 1. Flowchart of studies' selection process.

A value of k statistic was calculated to describe the extent to which the assessments by the two reviewers were the same. The calculated k value (0.85) showed an excellent level of agreement between reviewers.

Table 1. Main characteristic of included studies.

AUTHOR/YEAR COUNTRY	MILLING MACHINE (N.MILLED)	N. PRINTED SURGICAL GUIDES	3D PRINTER	3D-PRINTING LAYER THICKNESS (MICRON)	ORIENTATION	PARAMETER FOR ACCURACY MEASUREMENT	SCAN OF PRINTED SURGICAL GUIDES	SUPERIMPOSITION	SURFACE ACCURACY (TRUENESS)	SURFACE ACCURACY (PRECISION)	LDSASADM
ABDUO 2020 [8] Australia	Roland DWX-51D (10)	10 10	ProJet 3510 DP Pro, 3D System (DLP); Zortrax M200 3D, Zortrax (FFF)	32 (DLP); 100 (FFF)	0°	Root Mean Square	Laboratory scanner (not otherwise specified)	GeoMagic Studio	Yes (internal surface)	NA	Yes NA
CHEN 2019 [24] USA		10 10 10	Form 2; Formlabs Inc (Somerville, MA, United States), (SLA); Objet Eden260VS, (PO LYJET); ProX DMP 200 (DMP)	NA	0°	Root Mean Square	7Series	Geomagic Control X	Yes (internal surface)	Yes (internal surface) (percentage of measurement data points within 1 standard deviation of mean RMS values)	NA NA
DALAL 2012 [22] USA		60	Form 2, Formlabs	50; 100	0°; 45°; 90°	Absolute mean discrepancy	iCAT FLX V10	Geomagic Control X	Yes (internal surface)	Yes (variance of discrepancy)	Yes Yes
KOCH 2019 [25] USA		20 10 10	Form 2; Formlabs (SLA); ProJet 3510 DP Pro, 3D System (MJP); Objet Eden260VS (Polyjet)	25(SLA); 16 (Polyjet, Mulijey)	0°	Mean 3D deviation	TRIOS 3,3 Shape	Geomagic Qualify 12.0	Yes (entire surface)	Yes (entire surface) (Deviation and distribution of results)	NA NA
MUKAI 2021 [29] Brasil	Sirona MCXL (10)	10	Perfactory P4K Life Series, Envisiontec	NA	45°	Average mismatch	StereoSCAN 3D R8	Optocat software	Yes (entire surface)	Yes (entire surface)	NA NA
RUBAYO 2020 [26] USA		50	Form 2, Formlabs Inc	NA	0°; 30°; 45°, 60°; 90°	Root Mean Square	7Series Model and Impression Scanner	Geomagic Design X	Yes (internal surface)	NA	NA NA
RUBAYO 2020 [26] USA		50	Form 2, Formlabs Inc	NA	0°; 30°; 45°, 60°; 90°	Root Mean Square	7Series Model and Impression Scanner	Geomagic Design X	Yes (internal surface)	NA	NA NA
WEGMÜ LLER 2021 [28] Switzerland		10 10 10 10	Duplicator 7 Plus (DLP); Ultimaker 3 Ext. (FFF); Form 3 (SLA); Objet30 Prime (Polyjet)	50 (DLP); 100 (FFF); 50(SLA); 28 (Polyjet)	30–45° (DLP); NA (FFF); 30–45° (SLA); Various angulatio ns (Polyjet)	Root Mean Square	EinScan SP, SHINING 3D Tech. Co.	Materialise 3-Matic v. 14.0. Materialise, Leuven, Belgium	Yes (entire surface)	NA	NA NA
ROUZÈ L'ALZIT 2021 [29] France		12+2 12 12 12 12	Rapid Shape D40 (DLP-1); Cara Print 4.0 (DLP-2); Raise 3D Pro2 (FFF); Form 2 (SLA); Stratasys J750 (Polyjet); Prodways P1000 (SLS)	0° (DLP); 60° (FFF); 15° (SLA); NA (Polyjet); 0° (SLS);	Root Mean Square	CARES 7 Series; Straumann group	Geomagic Control X	Yes (internal surface)	Yes (internal surface)	NA	NA

Table 1. *Cont.*

AUTHOR/YEAR COUNTRY	MILLING MACHINE (N.MILLED)	N. PRINTED SURGICAL GUIDES	3D PRINTER	3D-PRINTING LAYER THICKNESS (MICRON)	ORIENTATION	PARAMETER FOR ACCURACY MEASUREMENT	SCAN OF PRINTED SURGICAL GUIDES	SUPERIMPOSITION	SURFACE ACCURACY (TRUENESS)	SURFACE ACCURACY (PRECISION)	LDSASADM	
SHAH 2021 [30] India		10	NA	NA	NA	NA	Medit T300; MEDIT	exocad; exocad GmbH	NA	NA	Yes	Yes
TAHIR 2022 [31] Australia		30	MoonRay S, SprintRay Inc, LA, CA, USA	20	0°; 45°; 90°	Root Mean-Square	Identica T300, Medit Identica, DT Technologies	(CloudCompare, EDF R&D, Paris, France)	Yes (internal surface)	Yes (internal surface)	NA	NA

LDSAM: Linear deviation at the sleeve access midpoint; SAD: Sleeve angular deviation; DLP: Digital light processing; FFF: Fused filament fabrication; SLA: Stereolithography; PJ: PolyJet; MJ: MultiJet; DMP: Direct metal printing; SLS: Selective laser sintering.

3.2. Studies Features

The included studies were published between 2018 and 2022. All eleven studies analyzed printed surgical guides (378 surgical guides), while only two studies [8,16,17,19] analyzed both printed and milled templates (20 surgical guides); none of the studies exclusively investigated milled guides.

The most analyzed 3D printing technology was the Stereolithography—SLA (172 guides) [22,24–26,28,30], followed by the digital light processing—DLP (68 guides) [8,19,27,29,31], the polyjet (42 guides) [24,25], the fused filament fabrication—FFF (40 guides) [8,28,29], SLS (12 guides) [29], and the multijet (10 guides) and direct metal printing—DMP (10 guides) [24,25]. Regarding the subtractive technology, 20 milled surgical guides were analyzed [8,19]: in both studies starting from a single model, 10 surgical guides were fabricated using both milling and 3D printing based on digital light processing (DLP) technology; the study by Abduo et al. [8] included a third group of 3D-printed surgical guides based on fused filament fabrication (FFF) technology.

Four studies [19,25,27,29] investigated the global surface accuracy and reported the data addressed as trueness and precision (except Wegmuller et al. [28], which focused only on the trueness), whereas six studies [8,22,24,26] investigated the internal surface; among the latter, four studies [22,24] examined both the trueness and the precision. Three studies [8,22,30] investigated the accuracy of the position of the sleeves; in particular, Dalal et al. [22] and Shah et al. [30] reported the data of the linear and angular deviation of the sleeves, and Abduo et al. [8] reported the data of the linear deviation (horizontal and vertical) at the sleeve access midpoint.

Different parameters were used for the accuracy measurement: the average mismatch [19], the root mean square (RMS) [8,24,26,28,29,31], the absolute mean discrepancy [22], the mean 3D deviation [25], the mean distance, and the absolute mean distance [27]. It should be considered that Koch et al. [25], Mukai et al. [19], and Sommacal et al. [27] used different terms for the accuracy parameter (mean 3d deviation, average mismatch, and mean distance, respectively), referring to the same measurement method.

3.3. Risk of Bias Assessment

The risk of bias within studies is summarized in Table 2. The studies had a medium to high risk of bias. It should be considered that in the study by Abduo et al. [8], although sample size calculation was not reported, a sample of the same size of the study by Mukai et al. [19] was investigated. In addition, in the study by [8], there are unclear methodological aspects: for example, the content in Tables 1 and 2 is referred to as "standard deviation" in the tables' legends, which is described as "the average for each group of the standard deviation found in each sample". Moreover, although Dalal et al. [22] analyzed the linear and angular deviation of the sleeves, the long axis of the sleeves is used to estimate both the angular and linear deviation; Shah et al. [30] reported the linear deviation by not identifying the vertical and horizontal errors.

Table 2. Parameters used to assess included studies' risk of bias.

AUTHOR	YEAR	SAMPLE SIZE CALCULATION	DETAILS REGARDING 3D PRINTING (LAYER THICKNESS, ORIENTATION OF THE SURGICAL GUIDE ON THE PRINTING PLATFORM)	DETAILS REGARDING MILLING PROCESS/STRATEGY	DETAILS REGARDING MILLING PROCESS/STRATEGY	BLINDING OF THE EVALUATION	MEASURING THE ACCURACY AT DIFFERENT PORTIONS OF THE SURGICAL GUIDE (SURFACE, SLEEVE	STATISTICAL ANALYSIS CARRIED OUT
ABDUO [8]	2020	No	Yes	No	No	Yes	Yes	Medium
CHEN [24]	2019	No	No	NA	No	No	Yes	High
DALAL [22]	2012	Yes	Yes	NA	No	Yes	No	Medium
KOCH [25]	2019	No	Yes	NA	No	No	No	High
MUKAI [19]	2021	Yes	No	No	No	No	Yes	High
RUBAYO [26]	2020	Yes	No	NA	No	No	Yes	High
SOMMACAL [27]	2018	No	Yes	NA	No	No	Yes	High
WEGMÜ LLER [28]	2021	No	Yes	NA	No	No	Yes	High
ROUZ'E L' ALZIT [29]	2021	No	Yes	NA	No	No	Yes	High
SHAH [30]	2021	No	No	NA	No	No	No	High
THAIR [31]	2022	Yes	Yes	NA	No	No	Yes	Medium

3.4. Synthesis of Results

The included studies were very heterogeneous (Table 1) in terms of the methodology and equipment used. In particular, eleven studies investigated the accuracy of printed surgical guides (unevenly between studies) by evaluating the different printing technologies [8,24,25,27–29], printing angle orientations [22,26,31], and printing thicknesses [22]. Two studies [8,19] compared the accuracy of printed to milled surgical guides. Furthermore, the different parameters used for the accuracy measurements made their results not comparable. Therefore, a meta-analysis was not appropriate, and the studies' results for surface accuracy and deviation at the sleeve access are reported in Tables 3 and 4, respectively.

Table 3. Surgical guides surface accuracy.

AUTHOR/ YEAR	MANUFACTURING TECHNIQUE	GLOBAL SURFACE ACCURACY (TRUENESS)	GLOBAL SURFACE ACCURACY (PRECISION)	INTERNAL SURFACE ACCURACY (TRUENESS)	INTERNAL SURFACE ACCURACY (PRECISION)
ABDUO 2020 [8]	DLP			0.23 ± 0.03	
	FFF			0.28 ± 0.06	
	Milling			0.21 ± 0.03	
CHEN 2019 [24]	SLA			0.22 ± 0.08	87.13 ± 3.91%
	Polijet			0.12 ± 0.025	92.76 ± 1.52%
	DMP			0.19 ± 0.035	89.75 ± 1.92%
DALAL 2012 [22]	SLA			0.055 ± 0.001 (0°-50 micron) 0.052 ± 0.002 (45°-50 micron) 0.061 ± 0.015 (90°-50 micron) 0.098 ± 0.01 (0°-100 micron) 0.084 ± 0.01 (45°-100 micron) 0.09 ± 0.006 (90°-100 micron)	
KOCH 2019 [25]	SLA	−0.013 ± 0.012 (Group1); 0.009 ± 0.015 (Group2)			
	Polijet	(−) 0.014 ± 0.016			
	Multijet	(−) 0.024 ± 0.008			
MUKAI 2021 [19]	DLP	0.02 ± 0.37			
	Milling	0.034 ± 0.112			

Table 3. *Cont.*

AUTHOR/ YEAR	MANUFACTURING TECHNIQUE	GLOBAL SURFACE ACCURACY (TRUENESS)	GLOBAL SURFACE ACCURACY (PRECISION)	INTERNAL SURFACE ACCURACY (TRUENESS)	INTERNAL SURFACE ACCURACY (PRECISION)
RUBAYO 2020 [26]	SLA			0.048 ± 0.007 (0°); 0.067± 0.009 (30°); 0.053 ± 0.012 (45°); 0.079 ± 0.016 (60°); 0.097 ± 0.017 (90°)	
SOMMACAL 2018 [27]	DLP	0.067 ± 0.008 (AMD); −0.011 ± 0.013 (MD)	0.095 ± 0.036		
WEGMÜLLER 2021 [28]	FFF		0.093 ± 0.012 (AMD); −0.023 ± 0.023 (MD)	0.147 ± 0.018	
	DLP		0.20 ± 0.11		
	FFF		0.03 ± 0.18		
	SLA		0.11 ± 0.06		
	Polijet		0.04 ± 0.07		
ROUZ'E L'ALZIT 2021 [29]	DLP-1			0.0643 ± 0.008 (SE); 0.106 ± 0.024 (LE)	0.064 ± 0.007 (SE); 0.101 ± 0.021 (LE)
	DLP-2			0.0755 ± 0.0139 (SE); 0.986 ± 0.0255 (LE)	0.0643 ± 0.009 (SE); 0.098 ± 0.0122 (LE)
	FFF			0.104 ± 0.0222 (SE); 0.139 ± 0.0224(LE)	0.0951 ± 0.012 (SE); 0.129 ± 0.020 (LE)
	SLA			0.0677 ± 0.0106 (SE); 0.0931 ± 0.0132 (LE)	0.0643 ± 0.009(SE); 0.098 ± 0.012(LE)
	Polijet			0.0704 ± 0.0054(SE); 0.109 ± 0.0186 (LE)	0.0702 ± 0.0054 (SE); 0.110 ± 0.0194 (LE)
	SLS			0.0979 ± 0.0136 (SE); 0.125 ± 0.0215 (LE)	0.0978 ± 0.013 (SE); 0.111 ± 0.0258 (LE)

Table 3. *Cont.*

AUTHOR/ YEAR	MANUFACTURING TECHNIQUE	GLOBAL SURFACE ACCURACY (TRUENESS)	GLOBAL SURFACE ACCURACY (PRECISION)	INTERNAL SURFACE ACCURACY (TRUENESS)	INTERNAL SURFACE ACCURACY (PRECISION)
SHAH 2021 [30]	SLA	NA	NA	NA	NA
THAIR 2022 [31]	DLP			0.1007 ± 0.0097 (0°); 0.114 ± 0.0076 (45°); 0.1203 ± 0.0076 (90°)	0.069 ± 0.0064 (0°); 0.0773 ± 0.0098 (45°); 0.0824 ± 0.0171 (90°)

LDSAM: Linear deviation at the sleeve access midpoint; SAD: Sleeve angular deviation; DLP: Digital light processing; FFF: Fused filament fabrication; SLA: Stereolithography; PJ: PolyJet; MJ: MultiJet; DMP: Direct metal printing; SLS: Selective laser sintering; SE: Small-Extend surgical guides; LE: Large-Extend surgical guides; AMD: Absolute mean deviation; MD: Mean deviation.

Table 4. Deviation at the sleeve access midpoint of investigated surgical guides.

AUTHOR/ YEAR	MANUFACTURING TECHNIQUE	VERTICAL DEVIATION AT THE SLEEVE ACCESS MIDPOINT	HORIZONTAL DEVIATION AT THE SLEEVE ACCESS MIDPOINT	SLEEVE ANGULAR DEVIATION
ABDUO 2020 [8]	DLP	0.4 ± 0.17 mm (ANT); 0.18 ± 0.06 mm (POST)	0.23 ± 0.07 (ANT); 0.22 ± 0.07 (POST)	NA
	FFF	0.41 ± 0.16 mm (ANT); 0.44 ± 0.09 mm (POST)	0.18 ± 0.13 (ANT); 0.16 ± 0.06 (POST)	NA
	Milling	0.25 ± 0.10 (ANT); 0.05 ± 0.04 (POST)	0.11 ± 0.04 (ANT); 0.14 ± 0.05 (POST)	NA
DALAL 2012 [22]	SLA	0.010 ± 0.003 (0°-50 micron) 0.0081 ± 0.003 (45 -50 micron); 0.012 ± 0.005 (90°-50 micron); 0.01 ± 0.005 (0°-100 micron); 0.016 ± 0.004 (45°-100 micron); 0.022 ± 0.002 (90°-100 micron)	0.010 ± 0.003 (0°-50 micron); 0.0081 ± 0.003 (45°-50 micron); 0.012 ± 0.005 (90°-50 micron); 0.01 ± 0.005(0°-100 micron); 0.016 ± 0.004(45°-100 micron); 0.022 ± 0.002(90°-100 micron)	1.29± 0.30° (0°-50 micron); 0.64 ± 0.13° (45°-50 micron); 0.56 ± 0.21° (90°-50 micron); 1.57 ± 0.29° (0°-100 micron); 0.86 ± 0.14° (45°-100 micron); 1.02 ± 0.31° (90°-100 micron)
SHAH 2021 [30]	DLP	0.040 ± 0.018 *		1.36 ± 0.74°

DLP: Digital light processing; FFF: Fused filament fabrication; SLA: Stereolithography; * Absolute linear deviation.

3.5. Accuracy of Printed Guides

Six studies compared the surgical guides produced via different printing technologies [8,24,25,27–31]. In particular, Abduo et al. [8] analyzed the DLP and the FFF (also comparing them with the milling, as reported in the next paragraph), reporting data in terms of the accuracy of the internal surface (trueness); although the DLP had greater accuracy than the FFF, there was no statistically significant difference ($p = 0.12$). Regarding the linear deviation at the sleeves' access midpoint, stratified for the anterior (central incisor position) and posterior (first molar position) sleeves, the results showed that for the horizontal errors of the sleeves, the FFF is more accurate than the DLP, although there is no statistical significance. Conversely, considering the vertical errors, DLP was more accurate than the FFF, although there was statistical significance only for the sleeves of the posterior implants ($p < 0.001$).

Chen et al. [24] compared SLA, Polyjet, and DMP by evaluating the accuracy of the surgical guides immediately after production and after a 1-month storage, in terms of the accuracy of the internal surface. The studies' results indicated that the Polyjet group had greater accuracy (trueness) than the DMP ($p < 0.001$) and SLA (not statistically significant, $p = 0.12$), as well as in terms of reproducibility/precision Polyjet showed better results than the DMP ($p = 0.002$) and SLA ($p = 0.008$). The results were confirmed after one month, showing significantly greater accuracy (trueness) of Polyjet compared to DMP and SLA ($p = 0.025$ and $p = 0.005$, respectively). Furthermore, the dimensional stability of the guides after one month was analyzed, showing a significant increase in the RSM for SLA and Polyjet ($p < 0.001$ and $p = 0.011$, respectively) unlike DMP ($p = 0.981$), which therefore showed greater dimensional stability.

Koch et al. [25] analyzed three different printing technologies: 2 SLA groups, 1 Multijet, and 1 Polyjet, evaluating the accuracy of the entire surface (trueness). The results indicated that the SLA has a higher accuracy than the other printing technologies, followed by Polyjet and Multijet, and a statistically significant difference between the groups was reported ($p = 0.0016$), although only the p-values of the overall analysis are reported and not those of the individual comparisons. The results also showed that there was a difference between the two SLA groups ($p = 0.0041$) and that the Multijet group had the highest precision, followed by the two SLA groups and the Polyjet one.

Sommacal et al. [27] compared the FFF print with the DLP print by evaluating the trueness and precision (using 80% quantile) of the surgical guides in terms of the entire surface. The study reported that DLP has greater accuracy than the FFF in terms of trueness ($p = 0.001$) and precision ($p = 0.015$).

Wegmuller et al. [28] investigated the Polyjet, SLA, FFF, and DLP technology in terms of the entire surface's accuracy. The results showed that the Polyjet group had the lowest RMS, followed by SLA, FFF, and DLP, with a statistically significant difference between the groups except between Polyjet and SLA.

Rouzè l'Alzit et al. [29] evaluated the accuracy of five printing technologies (DLP, FFF, SLA, Polyjet, and SLS), comparing six groups (as two DLP printers are used) in terms of trueness and precision of the internal surface. Each group consisted of two types of surgical guides: small-extend surgical guides (limited to the two teeth adjacent to the implant site) and large-extend surgical guides (full-arch guide). Regarding the small-extend surgical guides, the DLP-1 and SLA technology had the greatest accuracy, while the SLS and FFF groups had the lowest, both for trueness and precision; significant differences were found only in the comparison between the two more accurate and the two less accurate technologies. About the large-extend surgical guides, the DLP-2 and SLA technology had the greatest accuracy, while the SLS and FFF group had the lowest, both for trueness and precision; significant differences were found only in the comparison between SLA and FFF (trueness) and between DLP-2 and FFF (precision). Furthermore, this study is the only one to compare within each printing technology whether the extension of the surgical guide can affect the accuracy concluding that small-extend surgical guides have greater accuracy than the large-extend surgical guides for both trueness and precision;

there was statistical significance for all groups except for the DLP-2 group (trueness) and the DLP-1 and SLS group (precision).

Three studies [22,26,31] investigated the influence of the orientation of the printing angle on the accuracy of the printed surgical guides produced with SLA (Rubayo et al. [22,26], Dalal et al. [22]) and DLP (Thair et al. [31]) technology. All studies evaluated the accuracy of the internal surface in terms of trueness, and only Tahir et al. [31] considered the precision; moreover, Dalal et al. [22] evaluated the linear and angular deviation of the long axis of the sleeves. In particular, the first study [26] analyzing five groups of surgical guides printed at 0°, 30°, 45°, 60°, and 90° found that the 0° and 45° groups had the greatest accuracy, followed by the 30°, 60°, and 90° groups ($p < 0.05$). There were no statistically significant differences between 0° and 45° ($p = 0.341$) and between 30 and 60 ($p = 0.069$). Dalal et al. [22] and Tahir et al. [31] compared three groups at 0°, 45°, and 90°; the first [22] indicated that the 45° group had a better accuracy than the 0° and 90° groups in terms of intaglio surface accuracy ($p < 0.001$); instead, the second [31] revealed that the 0° group has statistically significant better accuracy than the other two groups for both trueness and precision. About the linear deviation of the guide sleeves, Dalal et al. [22] showed that it increased with the increasing printing angle and that the 45° group had a smaller angular deviation of the cylinders, compared with the 0° and the 90° groups.

In addition, Dalal et al. [22] was the only one to examine the influence of printing layer thickness on the accuracy of surgical guides. Setting a print thickness at 0.05 mm and 0.1 mm for each of the three printing angulations, the results showed that the 0.05 mm thickness had greater accuracy than the 0.1 mm one, in terms of intaglio surface accuracy ($p < 0.001$) in each of the printing angulation.

Regarding the linear and angular deviation of the cylinders, the results show that the printing thickness at 0.05 mm had a smaller deviation compared to 0.1 mm, both for the linear deviation and for the angular deviation (except at 0° of printing, $p = 0.05$).

3.6. Printed Guides vs. Milled Guides

For the surface accuracy, Mukai et al. [19] did not find significant differences between milling and 3D-printing, either for trueness or precision; nonetheless, a very high dispersion (0.467 mm and 0.37 mm for milling and 3D printing, respectively) around the average mismatch (0.002 mm and 0.02 mm for milling and 3D printing, respectively) were reported. No data were reported specifically for the internal surface accuracy, although the evaluation of figures in the paper shows an extensive deviation on the internal side. Conversely, Abduo et al. [8] reported significant differences for RMS between the milled and 3D-printed internal surface of the investigated surgical guides, whereas there were no significant differences between DLP and FFF printing technology.

In the latter study, the data regarding the horizontal and vertical linear deviation of the sleeve access midpoint, stratified for the anterior (central incisor position) and posterior (first molar position) sleeves, were reported. For both the vertical and horizontal deviations, in both the anterior and posterior sleeves, the milled surgical guides had a significantly lower deviation than the 3D-printed ones; differences between 3D printing technologies were significant for the vertical deviation in the posterior sleeves. Comparisons by zone (i.e., anterior versus posterior sleeves) showed significant differences only for the vertical deviations in the milled and DLP-printed surgical guides.

4. Discussion

Potential inaccuracies occurring at the manufacturing stage of surgical guides may cause discrepancies between planned and actual implant positions, contributing to compromising the outcomes and safety of guided dental implant surgery. The purpose of this systematic review was to investigate the accuracy of the surgical guides for implant surgery, which is estimated by aligning the STL file of the scanned surgical templates to the planned STL file to determine the trueness and precision of the underlying fabrication process, to evaluate which factors affect the accuracy of each technology and which of the two manufacturing processes provides the most accurate guides.

The trueness refers to the closeness of agreement between the average value obtained from a series of test results and a reference value; the precision refers to the closeness of agreement between the independent test results obtained under stipulated conditions [32].

From the analysis of the available studies, it emerged that there was very little data to answer the addressed PICO question: which of the two technologies reported for the processing of surgical guides, the subtractive one and the additive one, have better accuracy?

The studies that analyze this issue were partially discordant; the study by Abduo [8] et al. found a significantly better accuracy for the milled surgical guides, for all the investigated outcomes (internal surface accuracy, vertical fit discrepancy, seating distortion, and vertical and horizontal deviations at the sleeve access midpoint), although Mukai et al. [19] argues that the milled guides have only better accuracy and that there are no differences in terms of trueness. However, 3D printing had an advantage over milling in terms of costs and in dental applications for large-scale custom facial appliances in patients with craniofacial disorders, which may be a viable option to fabricate large scale appliances with larger dimensions than the implant guides [33].

Some of the included studies [8,19,22,24–29,31] investigated some factors of the printing manufacturing process that could affect the accuracy of the printed surgical guides;

there are no included studies investigating the potential variables affecting the accuracy of the milled ones.

4.1. Printing Technology

Different additive manufacturing technologies and material combinations seem to affect the accuracy, reproducibility, and stability of the CAD-CAM surgical templates [24], although the results of the included studies are slightly contrasting. It was proposed that professional 3D printers (or industrial-level 3D printers), in particular DLP [8,27,29] and Polyjet [24,28] technologies, could be more accurate than the desktop/home 3D printers as SLA [24], SLS [29], and FFF [8,24,27,29], as regards the trueness of the surface guides [8,24,27], and that among these, the SLA technology had more accuracy than the others [29].

These results are partially in contrast with those emerged by Wegmuller et al., who showed that Polyjet technology is the most accurate, but argues that professional DLP printing is the least accurate of all those examined, and also with those emerging by Koch et al. [25,28], according to which SLA is better in terms of Polyjet and Multijet technologies (it is noteworthy that in the study there was a bias in the statistical analysis since post hoc analysis is not reported, thus it is not clear which of the analyzed groups differed significantly from the others).

Instead, there was agreement in supporting that the precision of the surface accuracy of the guides produced by professional printers is greater than those produced by desktop printers [24,25,27,29].

Regarding sleeve deviation, there are few data about which printing technology is more accurate; Abduo et al. [8] found that DLP, compared to FFF, had a significantly lower vertical deviation at the sleeve access.

Some of the reasons explaining the better performance of professional printers could be related to the intrinsic higher printing resolution (due to hardware differences: the finer movements of steeper motors [34], the smaller diameter of the laser or extrusion nozzle [24], and support for thinner printing layers [24]) or to the postprocessing requirements, as experience of personnel in a professional manufacturing setting [27].

4.2. Printing Layer Thickness

The analysis of the influence of the printing layer thickness, investigated only for the SLA technology in one included study [22], is consistent with the general knowledge that the smaller the printing layer, the more accurate the printing will be; therefore the setting at 50 µm printing thickness produced more accurate surgical guides than the 100 µm one for all investigated outcomes (internal surface accuracy, and the vertical and horizontal deviations at the sleeve access midpoint) [22].

4.3. Printing Angulation

At the same thickness, the printing angulation appeared to affect the accuracy of the surgical guides [22,26]. All authors agreed that the 0° orientation, in both the DLP [31] and SLA [22,26] technology, was associated with less internal surface discrepancy from the SLT file in terms of trueness [26,31] and precision [31]. It was proposed that the 0° orientation, (orienting horizontally the largest dimension of the surgical guides) allows for maximizing the used area on the printing platform, increasing the support structures, reducing the number of printing increments, and minimizing the printing duration [31]. The reason why an increased build angle negatively affected the accuracy of the 3D-printed surgical template could be related to the displacing by gravity of the incomplete polymerized resin and to the surface tension of the liquid photopolymerizing resin in the printing vat.

Regarding the influence of this factor in the deviation of the sleeves' access, there is not enough data to answer: Dalal et al. [22] concluded that "the linear guide tube deviations increased with an increase in the angle of printing" and "the 45° group had the least angulation deviations of the guide tube", but it should be noted that it was true and statistically significant only for the 100 µm group; instead, both statements were not valid for the 50 µm group. In addition, in this study [22], there could be concerns related to the statistical analysis as the post hoc analysis was not performed to determine which of the groups analyzed differs significantly from the others.

The present systematic review has limitations mainly related to the methodological heterogeneity between studies, which had employed different fabrication and scanning equipment, 3D-printing processing, software technologies for superimposition and measurements, target measurement areas, and, most of all, the parameter used for the accuracy measurements which made it not possible to perform a quantitative synthesis of the results. It has not been possible to conduct a meta-analysis that analyzed and summarized the overall results, or a network meta-analysis that would have allowed us to estimate the effect of each group on each other, even when they are not directly compared in the individual studies. Another important limitation is represented by the inaccuracy of the statistical analysis (especially in studies that presented more than the two groups and did not perform the post hoc tests necessary to identify the differences between the individual groups) which could lead to partial and misunderstood results.

5. Conclusions

Based on the findings from this systematic review, the qualitative assessment suggests that milling can achieve better results, at least in terms of reduced variation, although there is little evidence to address which manufacturing technology (milling or 3D printing) significantly provides more accurate surgical guides.

Similarly, it seems that, for additive technologies, several factors could influence the accuracy; the professional printing technologies including Polyjet and DLP, the printing angle at 0°, and the small printing thickness were mostly associated with better accuracy of the guides for implant surgery. Nonetheless, quantitative analysis was not possible, and no robust conclusion could be made.

An appropriate selection remains a sensible issue with significant clinical implications and needs further investigation. Future studies are encouraged to verify and quantify which factors in each manufacturing process influence the accuracy of the surgical templates and if there are differences between milling or 3D printing technologies. The accuracy of the surface (particularly the internal surface), the horizontal and vertical deviations at the sleeve access, as well as the angular deviations of the sleeves, should be evaluated both in terms of accuracy and veracity; it is recommended to report as many parameters as possible such as the average mismatch, the root mean square, the absolute mean discrepancy, the mean 3D deviation, the mean distance and the absolute mean distance. Furthermore, it would be interesting to evaluate and understand if other post-production factors, such as sterilization procedures, could affect the accuracy of the templates.

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