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ACCURACY OF DIGITAL TECHNOLOGIES IN IMPLANT PROSTHODONTICS

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“as long as we keep moving, we don’t notice
how tired we are, but only when we sit down.”

— Antal Szerb, *Journey by Moonlight*

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1. LIST OF ABBREVIATIONS

3D-printing	Three-Dimensional printing
CAD / CAM	Computer-Aided Design / Computer-Aided Manufacturing
CI	Confidence Interval
CMM	Coordinate Measuring Machine
ESP	Extraoral Stereophotogrammetry
GRADE	Grading of Recommendations Assessment, Development and Evaluation
IOS	Intraoral scanner
PICO	Population-Intervention-Comparator-Outcome
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROSPERO	International Prospective Register of Systematic Reviews
QUIN	Quality Assessment Tool for In Vitro Studies
RMS	Root Mean Square
RoB	Risk of Bias
SD	Standard Deviation
STL	Standard Tessellation Language

2. STUDENT PROFILE

2.1. Vision and mission statement, specific goals

My vision is to establish modern, simple, and patient-friendly workflows in implant prosthodontics with the highest possible accuracy. My mission to achieve this is to investigate the accuracy and efficacy of novel technologies in implant prosthodontics.

My specific goals are to investigate the accuracy of intraoral scanning and 3D printing in the fabrication of implant prostheses and to identify the most suitable methods.

2.2. Scientometrics

Number of all publications	7
Cumulative IF	36.7
Av IF/publication	5.24
Ranking (Scimago)	D1:5, Q1:2
Number of publications related to the subject of the thesis	2
Cumulative IF	6.5
Av IF/publication	3.25
Ranking (Scimago)	D1: 1, Q1: 1
Number of citations on Google Scholar:	30
Number of citations on MTMT (independent):	22
H-index:	3

2.3. Future plans

I plan to continue my research after my PhD defense. Besides further research, my main goal is to apply and implement my findings in my clinical work and solve more full arch implant cases based on research data. For more data and greater clinical value, I would like to shift my focus from the literature and in vitro research to in vivo clinical research. I am planning to establish workflows and protocols for the treatment of completely edentulous patients receiving full arch implant-supported prostheses.

3. SUMMARY OF THE THESIS

Digital methods, such as intraoral scanning and 3D printing, are increasingly used in the fabrication of implant-supported dental prostheses. Although these methods offer many advantages over conventional methods, their accuracy has been debated for years now. We aimed to conduct two meta-analyses to investigate the accuracy of these methods.

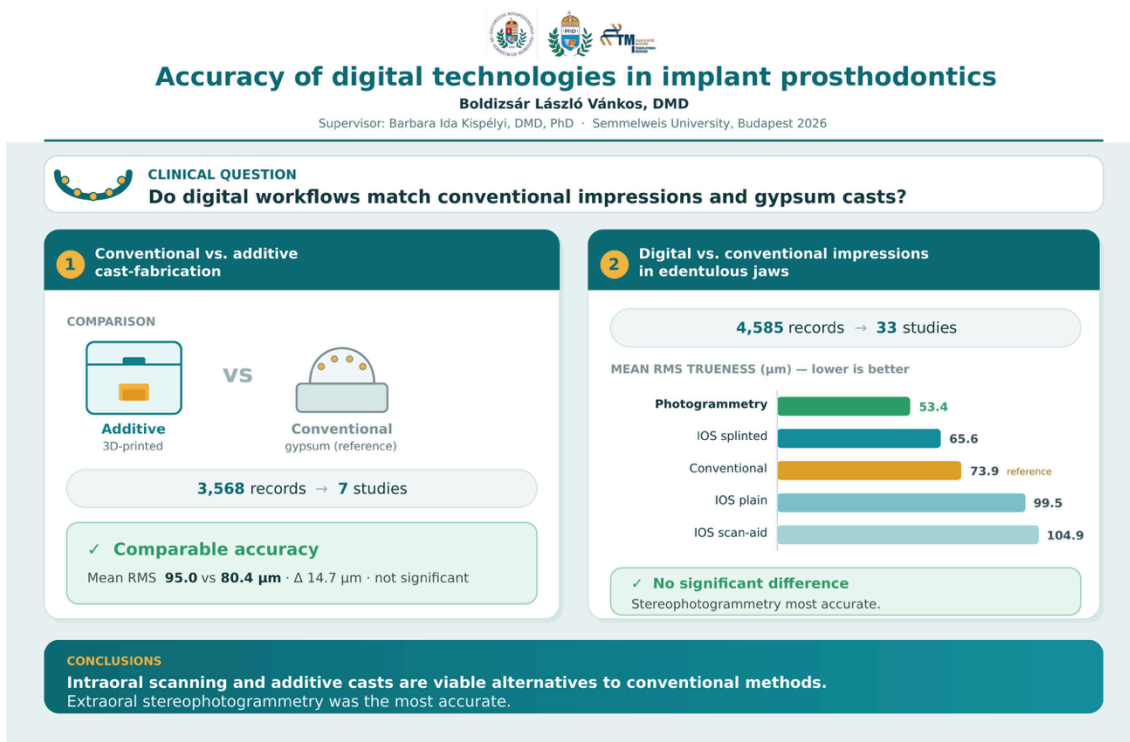
The first meta-analysis investigated the accuracy of intraoral scanning and additive model fabrication compared with the gold-standard open-tray impression and gypsum cast-fabrication.

In the second meta-analysis, we investigated the accuracy of different digital implant impression-taking methods compared with conventional open-tray impression-taking. Our study included intraoral scanning, extraoral stereophotogrammetry, and scanbody splinting.

The differences in accuracy between digital and conventional methods were not statistically significant. However, for full arch restorations, there were noticeable differences that might have clinical relevance.

In conclusion, our findings suggest that intraoral scanning and additive cast-fabrication are viable alternatives to the gold-standard conventional methods. Based on our results, extraoral stereophotogrammetry showed the most favorable trueness and precision point estimates.

4. GRAPHICAL ABSTRACT



5. INTRODUCTION

5.1. Overview of the topic

5.1.1. What is the topic

We investigate the accuracy of intraoral scanning and additive model-manufacturing in implant prosthodontics, focusing on edentulous, full arch cases (“All-on-X”).

5.1.2. What is the pRoBlem to solve?

The accuracy of digital methods compared to the conventional methods is not well described. We would like to investigate the accuracy of these methods regarding All-on-X cases.

5.1.3. What is the importance of the topic?

Digital dental technologies are gaining popularity for several reasons. They are more predictable and reproducible, less dependent on the human factor. In many cases, they offer a simpler, quicker, and more straightforward workflow. Using computer-aided design/computer-aided manufacturing (CAD/CAM) allows the use of special materials that cannot be machined via conventional technologies.

Conventional implant impression-taking and cast-fabrication, though considered the gold standard, are lengthy and complicated procedures. Digital impression-taking and cast-fabrication render the need for splinting the copings and for impression materials unnecessary. According to studies and surveys, patients tend to choose digital impressions over conventional methods for greater comfort and satisfaction.[1, 2]

However, digital dental systems are a significant investment that requires careful consideration. The accuracy of these systems is continually improving, but more data is needed to determine whether they can match well-proven conventional methods.

5.1.4. What would be the impact of our research results?

We would establish prosthetic treatment protocols based on accuracy data. These could facilitate and streamline the workflows of implant prostheses fabrication, significantly reducing treatment time and improving patient comfort.

5.2. Understanding the main differences between digital and conventional impression-taking and cast-fabrication methods

Accurate transfer of implant positions to the dental laboratory is fundamental to achieving predictable, functional, and long-lasting implant-supported prostheses. Impression-taking techniques aim to record the three-dimensional spatial relationships of implants with sufficient accuracy to fabricate restorations that fit passively, thus avoiding complications. However, these techniques differ markedly in their mechanisms, strengths, and intrinsic sources of error. As outlined in the two studies forming the basis of this thesis [3, 4], these methods are based on physical impact (conventional methods) or optical capture (digital methods).

Conventional impression techniques use elastomeric materials that physically engage impression copings. Their accuracy is influenced by material properties such as polymerization shrinkage, viscoelastic deformation, and stone expansion. Each conventional step - from impression-making to gypsum pouring and casting-adds potential points of distortion.[5-7] Digital impression methods however replace physical effects with optical data acquisition. Intraoral scanners (IOS) digitally capture surface geometry using structured light or confocal imaging, while advanced extraoral stereophotogrammetry (ESP) systems determine implant positions via triangulation of specially designed scan bodies. These systems help avoid many material-based inaccuracies, but they introduce new challenges as well, such as stitching errors and software-dependent reconstruction mistakes.

In terms of trueness and precision, evidence shows that for single-unit and short-span implant restorations, intraoral scanners (IOS) can achieve accuracy equivalent to or better than conventional methods.[8, 9] However, in full arch cases, digital accuracy varies more widely. IOS scans accumulate stitching errors over longer distances, whereas conventional impressions may perform better for large spans-although they

remain limited by material distortion.[10, 11] Extraoral stereophotogrammetry has emerged as one of the most accurate digital techniques for full arch implant cases, often surpassing both IOS and conventional impressions.[10]

Digital methods offer advantages in patient comfort, workflow efficiency, and communication. Yet conventional impressions remain essential in certain clinical contexts and offer cost-effective reliability. Understanding the strengths and limitations of each method is crucial for selecting the appropriate technique for any given implant scenario.

5.2.1. Impression-taking and model-making

In clinical work, impressions are taken to provide dental technicians with an accurate copy of the patient's oral structures. In the conventional workflow, impression-taking is always followed by cast-fabrication, creating a model to work on. Measuring the accuracy of impression-taking on its own is difficult, therefore, casts are usually measured, summarizing all inaccuracies of the two steps.

When working with digital technology, however, it is easy to conduct measurements directly from the scan files, without the need for model fabrication. This means there is one fewer step, so the comparison between the two methods inherently introduces a certain error.

To fabricate physical casts from scan files in most cases additive manufacturing - three-dimensional printing (3D printing) technologies are used. If we measure the printed casts, the odontotechnological steps are equivalent to those of conventional methods, so deviations in cast-fabrication are included in the final measurements.

For different uses of casts, several accuracy ranges have been described. For diagnostic or educational purposes, a threshold as high as 300-500 μm is sufficient.[12, 13] For orthodontic purposes (e.g., aligner fabrication), casts with deviations of less than 250 μm are recommended.[12, 14, 15] A strict limit should be applied for prosthodontic purposes; however, digitally machined prostheses are designed and fabricated from the scan files, not the printed models. Printed casts are often used to adjust the occlusal and interdental contact points and individually dye, finish, and polish prostheses.[16]

5.2.2. Conventional Impression Taking and Cast-fabrication Methods

Conventional implant impressions continue to play a vital role due to their predictable outcomes and long-established clinical protocols. They include two principal techniques-open-tray and closed-tray. In multi-implant or full arch cases, splinting of impression copings is often incorporated to enhance accuracy.

The open-tray technique involves perforating the impression tray so that impression copings can be unscrewed through the tray once the material has set. This ensures that the copings remain embedded within the impression. The dental technician subsequently attaches implant analogs directly to the copings within the impression, minimizing analog transfer errors. This method is particularly advantageous where implants are angulated or there are multiple implants next to each other. Its primary benefit is enhanced positional fidelity; however, disadvantages include increased complexity, the need for tray modification, longer chair time, and potential patient discomfort.

In the closed-tray technique, the impression tray remains intact. After the impression is removed, the impression copings remain attached to the implants intraorally. The clinician then unscrews these copings and inserts them into the impression before sending it to the laboratory. The technique is less clinically demanding and generally more comfortable for the patient, making it suitable for single- or short-span implant cases. However, re-inserting the copings introduces opportunities for rotational and angular inaccuracies, particularly in cases with diverging implants.

In more complex scenarios, such as full arch, edentulous, or long-span implant restorations splinting impression copings is strongly recommended. Using acrylic resin or prefabricated bars to stabilize the copings rigidly reduces micro-movement during impression removal and analog insertion. Numerous studies confirm that splinting consistently improves precision and trueness across full arch impressions.[17, 18]

Despite their widespread adoption, conventional techniques inherently carry material-related distortions: polymerization shrinkage, thermal expansion, elastic deformation, and stone-setting expansion all contribute to cumulative inaccuracies.[19, 20] Laboratory procedures including analog insertion, model trimming, and cast storage represent further sources of error. Additionally, patient-related limitations such as gag

reflex, limited mouth opening, and intolerance to impression materials can complicate the procedure.

Nonetheless, conventional impressions remain RoBust, predictable, and accessible for all. They are especially valuable in scenarios where bleeding, high reflectivity, or limited intraoral space inhibits digital scanning.

5.2.3. Digital Impression Taking Methods

Digital impression-taking methods have transformed implant dentistry by replacing material-based impressions with optical data acquisition. The two primary modalities are intraoral scanning and extraoral stereophotogrammetry, each offering unique workflows and clinical applications.

When used for implants, IOS employs structured light projection, laser scanning, or confocal microscopy to record the geometry of the scan bodies and adjacent tissues. The captured images are stitched into a unified 3D digital model using the scanner software. IOS systems offer significant advantages: reduced patient discomfort, immediate data visualization, elimination of material-related errors, faster workflow, and seamless integration with CAD/CAM fabrication. Digital files can be stored indefinitely, easily duplicated, and transmitted instantly to laboratories.

However, IOS accuracy depends on several factors: operator skill, scanning strategy, type and reflectivity of scan bodies, soft-tissue movement, and the scanner's optical resolution. A key limitation is error accumulation over long distances, as individual image frames are merged. This makes full arch scanning particularly challenging. Systematic reviews consistently report that IOS matches the accuracy of conventional methods for single-unit or short-span implants but may be less reliable for full arch reconstructions.[21, 22] Techniques such as scanbody splinting, controlled scan paths, and newer stitching algorithms help mitigate these issues.

Extraoral stereophotogrammetry has emerged as a highly accurate solution for capturing implant positions in full arch cases. This method uses specialized photogrammetric scan bodies with coded markers. Multiple fixed cameras capture images simultaneously, and implant coordinates are computed through geometric triangulation. Unlike IOS,

stereophotogrammetry is not affected by intraoral conditions, scanning distance, or surface reflectivity. Numerous in vitro and clinical studies have demonstrated its superior precision and trueness relative to both conventional impressions and IOS.[17, 23]

Extraoral stereophotogrammetry's main advantages include exceptional accuracy, minimal operator variability, rapid acquisition, and reliability across full arch multi-implant cases. However, the technology requires specialized equipment, additional software steps to merge implant coordinates with soft-tissue scans, and a higher initial investment. It is commonly used in advanced implant centers and full arch rehabilitation workflows.

Overall, digital impression-taking offers considerable advantages: improved patient comfort, reduced material costs, enhanced communication with laboratories, immediate error detection, and integration with virtual planning tools. Digital data are durable, easily archived, and compatible with modern manufacturing techniques such as milling and 3D printing. However, limitations include high equipment costs, learning curves, reliance on software ecosystems, and decreased accuracy in difficult intraoral environments (e.g., saliva contamination, restricted access, metallic reflections).

In summary, IOS is ideal for single implants and short-span restorations, while extraoral stereophotogrammetry is the most accurate method available for full arch implant recording. Digital workflows continue to advance, offering improved accuracy and efficiency, yet the selection of impression technique must be tailored to the clinical situation, available technology, and clinician experience.

6. OBJECTIVES

6.1. Study I Accuracy of conventional versus additive cast-fabrication in implant prosthodontics: A systematic review and meta-analysis of in vitro studies

We aimed to investigate the accuracy of additive cast-fabrication in implant prosthodontics.

We hypothesized that additive cast-fabrication would be less accurate in determining the position and orientation of implant analogs than conventional methods.

6.2. Study II - Accuracy of Digital and Conventional Implant Impressions in Edentulous Jaws: A Systematic Review and Meta-Analysis of In Vitro Studies

This systematic review and meta-analysis aimed to evaluate and compare the accuracy of conventional impression-taking, intraoral scanning, and extraoral stereophotogrammetry for implant-supported restorations in edentulous mandibular models.

According to our hypothesis, digital impression-taking methods would demonstrate lower accuracy than the gold-standard conventional impression method

7. METHODS

Both meta-analyses were prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) under the following registration numbers: CRD42022374972 (Study I) and CRD42023393091 (Study II).

Both research protocols were based on The Cochrane Handbook for Systematic Reviews [24] and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (PRISMA 2020).[25]

7.1. Study I - Accuracy of conventional versus additive cast-fabrication in implant prosthodontics: A systematic review and meta-analysis of in vitro studies

7.1.1. Systematic search and study selection

To investigate the accuracy of additive cast-fabrication, we used the Population-Intervention-Comparator-Outcome (PICO) question framework. Based on the framework, our search key was divided into three main domains: population data, intervention data, and comparator data. A systematic search was conducted in the following databases: PubMed (MEDLINE), EMBASE, and Cochrane Library (Cochrane Central Register of Controlled Trials [CENTRAL]) on November 12, 2022. The search was conducted without filters.

The following search keywords were used:

(implant OR implanted OR replica OR implant-prosthodontics OR implant prosthodontics) AND

(3D OR printing OR printed OR additive OR additively) AND

(gypsum OR stone OR conventional OR traditional) AND (model OR cast OR casts).

Removal of duplicate studies and selection were performed by two independent authors using the reference management tool EndNote X9.3.3 (Clarivate Analytics, Philadelphia, PA, USA) and Rayyan online selection tool.[26] Articles were first screened by title and abstract, followed by the full text. In cases of disagreement, a third author was involved in reaching a consensus. Interrater agreement was measured using Cohen's kappa. The selection process is documented in the PRISMA flowchart of selection.

After the selection process, backward citation chasing was performed to identify additional potential studies in the references of the eligible full-text articles. Due to the lengthy process of completing the study, a repeated search was conducted on May 5, 2023, to identify any additional articles on the topic.

7.1.2. Data collection process and data items

A standardized data collection sheet was developed through consensus among several methodological and clinical experts. All available data were collected into predefined tables by two independent investigators. The following data items were extracted: title, first author, year of publication, country, study design, main study findings, patient demographics, interventions, and outcomes.

7.1.3. Effect measure and synthesis methods

In our study, all statistical analyses were performed in accordance with Harrer et al.[27] The analyses were random-effects meta-analyses using a restricted maximum likelihood estimator.

The effect measures were linear and 3D deviations of the implant analogs. Most studies reported the average signed deviation (μm) of a prominent point on the implants relative to the expected position along three axes. However, several statistical challenges were encountered during the analyses. Although the vertical axis was well distinguished in the studies, the descriptions of the two horizontal axes were not uniform in all cases. Most articles reported the use of several different additive technologies. Therefore, the underlying true effects corresponding to the different outcomes in the same study were correlated. Also, in the case of a horizontal deviance pool, the sample errors on the two axes of the same measurement were correlated. To account for these correlations, a three-level model was fitted. In addition to between-study heterogeneity, within-study heterogeneity was also included, representing heterogeneity due to the use of different additive technologies. The RoBust approach of Pustejovsky[28] was included to circumvent the pRoBlem of unknown correlations between sample errors in the horizontal pool. An equal correlation was assumed between the measurements on the

two horizontal axes, and a RoBust correction was applied. For the control pools, a conventional two-level model was applied because the same technology was used for both axes.

The mean of the signed deviations can approach zero if both large positive and negative differences exist, however, they counter each other. Therefore, the means and standard deviations (SDs) of the absolute deviances were estimated for each outcome by using the corresponding formulas of the folded normal distribution. The analysis of absolute deviance is as important as, or more important than, that of the signed version. In the case of signed deviations, the raw or untransformed means were indicated, whereas in the case of absolute deviations, the estimated absolute means were indicated.

Root mean square (RMS) deviations, i.e., the root of the squared sum of deviations in all three axes, were also pooled from studies reporting them. In this case, a meta-analysis of the difference in the RMS between the two groups was also conducted. For studies reporting quartiles rather than the mean and SD, the methodology of Luo[29] and Wan[30] was used to estimate the mean and SD of the quartiles. In some cases, the corresponding data were extracted using WebPlotDigitizer.[31]

When there were no correlations between sampling errors within the studies, the between- and within-study I² and their sum, or the conventional I² square for control pools, were reported. For horizontal deviance pools, where the correlation structure was more complex, the data were simplified. For each study and technology, one of two correlated outcomes was randomly selected, and a multi-level model was fitted. The resulting between- and within-study I² statistics were reported.

7.1.4. Bias assessment and quality of evidence

Risk of bias (RoB) was assessed using the QUIN (Quality Assessment Tool for In Vitro Studies) RoB tool developed for in vitro dental studies.[32] It includes a 12-item checklist with scoring and grading options. Domains that are adequately specified in the article are worth two points, domains not adequately specified are worth one point, domains not specified are worth zero points, and domains that do not apply to the study are not rated. After scoring, each study was judged as having a low, medium, or high RoB.

As the GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework is tailored to the appraisal of clinical and population-level evidence, it is not directly suited to mechanistic or in vitro experimental research.[33] Consequently, GRADE was not applied in this thesis, and the quality of in vitro evidence was evaluated using methodological criteria appropriate for in vitro studies.

7.2. Study II Accuracy of Digital and Conventional Implant Impressions in Edentulous Jaws: A Systematic Review and Meta-Analysis of In Vitro Studies

7.2.1. Systematic search

A systematic literature search was conducted on the 15th of May 2025 in the following databases: PubMed (MEDLINE), EMBASE, Web of Science, and the Cochrane Library (Cochrane Central Register of Controlled Trials [CENTRAL]). Only articles published in English were included, and the reference lists of relevant articles were also screened. The search was conducted with no filters applied. A differently adapted search key was used in each database.

After screening and selection, backward citation chasing was performed to identify further potentially relevant studies from the references of the selected studies.

7.2.2. Study selection and data collection process

The study selection and data collection were both carried out by two independent reviewers. Initial screening was performed on titles and abstracts, followed by full-text selection. Interrater agreement was assessed with the use of Cohen's kappa. Disagreements were resolved through consultation with a third reviewer.

A data extraction sheet was developed with the help of methodological, statistical, and clinical experts. From the included studies, the following data items were collected: first author, year of publication, country of origin, study design, population details, key findings, intervention details, and reported outcomes.

7.2.3. Effect measure and synthesis methods

The effect sizes were different 3D deviations of implant analogs measured in micrometers. The analyses in our review were performed in accordance with Harrer et al.[27] The analyses performed are random-effects meta-analyses using a restricted maximum likelihood estimator.

The sample size, mean, and the standard deviation (SD) were extracted directly or indirectly from each study. A random-effects model with a generic inverse variance method was used to pool the data. To estimate the heterogeneity variance measure (tau squared), the restricted maximum-likelihood estimator was used with the Q profile method for confidence intervals.[6, 27]

Based on the various levels of subdivision of study arms and outcomes, the final choice was based on clinical and statistical aspects (i.e., data availability and structure).

In cases where multiple devices were used for the same sample within a study, we selected the “best” method when all other entry parameters were the same, based on a ranking list created by methodological and clinical experts in the field. To create a preference list of the intraoral scanners and impression-taking methods, several factors were considered, including the clinical commonness of use and accuracy.

7.2.4. Bias assessment and quality of evidence

Risk of bias was assessed independently by two authors using the QUIN tool (Quality Assessment Tool for In Vitro Studies)[32], which is specifically designed to evaluate RoB in in vitro dental research. The tool consists of a 12-item checklist with predefined scoring criteria: domains clearly described in the article receive 2 points, those insufficiently described receive 1 point, and domains not addressed receive 0 points. Items deemed not applicable to the study are excluded from scoring.

As the GRADE framework is tailored to the appraisal of clinical and population-level evidence, it is not directly suited to mechanistic or in vitro experimental research.[33] Consequently, GRADE was not applied in this thesis, and the quality of in vitro evidence was evaluated using methodological criteria appropriate for in vitro studies.

8. RESULTS

8.1. Study I - Accuracy of conventional versus additive cast-fabrication in implant prosthodontics: A systematic review and meta-analysis of in vitro studies

8.1.1. Study selection

Our systematic search yielded 3,568 articles. After removing duplicates, 2,993 articles were screened. Based on title and abstract screening, 39 articles were selected for full-text screening. Thirty-one papers were excluded based on the predefined eligibility criteria. The remaining eight articles were included in the systematic review, and seven articles were included in the statistical analysis. Interrater agreement was assessed using Cohen's kappa, with a score of 0.94 for title and abstract and 1 for full-text selection. The process of study selection was documented using the PRISMA flowchart of selection in Figure 1.

Figure 1 PRISMA flowchart of the study selection process for the systematic review in Study I, showing the number of records identified, screened, excluded, and included.

8.1.2. Study characteristics

The included articles were two-arm in vitro interventional studies using experimental gypsum or resin models as references. The reference model contained implants in two cases[34, 35] and laboratory implant analogs in six cases.[36-41] Two studies

investigated a completely edentulous maxilla with six to seven implant positions[36, 39], five studies investigated a partially edentulous maxilla with one to three implant positions[34-36, 38, 41], and one study investigated a partially edentulous mandible with two implant positions[40]. Four studies used laboratory-grade scanners[34, 36, 37, 39] and another four used intraoral scanners for digital impression-taking[35, 38, 40, 41]. For conventional technology, seven studies used open-tray impression technology with polyether or type-A silicone[34-37, 39-41], while one study used closed-tray impression technology with type-A silicone[38]. These studies used laboratory-grade optical and mechanical scanners to measure the positional accuracy of implant analogs. Five studies reported linear deviations of the analogs[34, 36-39], and five reported overall 3D or RMS deviations[35-37, 40, 41].

8.1.3. Results of the synthesis

8.1.3.1. *Accuracy outcomes – vertical displacement of implant analogs*

Vertical deviations were measured for five articles. Signed numbers were reported in four articles[34, 36-38], however, one article was excluded from the analysis because it contained only absolute values of the deviations[39]. The vertical displacement of the implant analogs in the control and intervention groups is shown in Figures 2 and 3, respectively. Positive and negative values indicate the direction of deviation along the vertical axis. Positive deviations indicate a more coronal position, and negative deviations indicate a more apical position. In the intervention group, the overall vertical mean deviation was -4.15 μm with a 95% confidence interval (CI) of [-24.88; 16.57], whereas in the control group, this value was 19.67 μm [95% CI, -32.71; 72.04]. Despite the large deviations, we included the results of Buda et al. as there were no notable methodological differences compared to other studies. These results can be explained by operator experience. In addition to signed deviations, pooled mean absolute deviation analysis was also performed, yielding 22.43 μm [95% CI, 8.33; 36.54] in the intervention group and 24.62 μm [95% CI, 0.00; 59.42] in the control group.

Figure 2 Forest plot of vertical displacement of implant analogs (μm) in the control group. Data were pooled from studies reporting signed and using estimated absolute deviations. Positive values indicate a more coronal position and negative values a more apical position of the analog relative to the reference. The pooled mean deviation was $19.67 \mu\text{m}$ (95% CI: -32.71 to 72.04) for the signed and 24.62 (95% CI: 0.00 to 59.42) in the absolute value group. [CI, confidence interval]

Figure 3 Forest plot of vertical displacement of implant analogs (μm) in the intervention group. Data were pooled from studies reporting signed and using estimated absolute deviations. Positive values indicate a more coronal position and negative values a more apical position of the analog relative to the reference. The pooled mean deviation was $-4.15 \mu\text{m}$ (95% CI: -24.88 to 16.57) for the signed and 22.43 (95% CI: 8.33 to 36.54) for the absolute value groups. [CI, confidence interval]

8.1.3.2. Accuracy outcomes – horizontal displacement of the implant analogs

The values of the two horizontal axes were pooled because the studies did not always clearly mark the axes, and the direction of the deviations had no real clinical significance. Three studies reported the horizontal displacement of analogs in two directions[36-38]. The horizontal deviation values for the control group are shown in Figure 4, and those for the intervention group are shown in Figure 5. The overall deviation in the intervention group was $21.29 \mu\text{m}$ [95% CI: -77.10 to 119.68]. The overall mean in the control group was $1.45 \mu\text{m}$ [95% CI: -32.26 to 35.15]. One outlier

in the control group had a mean of 61.60 μm [95% CI, 55.05; 68.15]. This could be explained by operator experience, the use of different 3D printing technologies by Mata-Mata et al.[38], or a different measurement method. An analysis of pooled mean absolute deviance was also conducted, yielding 26.96 μm [95% CI, 0.00; 70.81] in the intervention group and 23.14 μm [95% CI, 14.12; 32.15] in the control group. The overall mean is promising, with almost no deviation; however, the confidence interval should be considered high. In addition, the pooled absolute means are of great help for correct interpretation.

Figure 4 Forest plot of horizontal displacement of implant analogs (μm) in the control group. Data were pooled from three studies reporting deviations along two horizontal axes; values from both axes were combined. The pooled mean deviation was 1.45 μm (95% CI: -32.26 to 35.15 for the signed and 23.14 (95% 14.1 to 32.15) in the absolute value groups. [CI, confidence interval]

Figure 5 Forest plot of horizontal displacement of implant analogs (μm) in the intervention group. Data were pooled from studies reporting deviations along two horizontal axes; values from both axes were combined. The pooled mean deviation was $21.29 \mu\text{m}$ (95% CI: -77.10 to 119.68 for the signed and 26.96 (95% CI: 0.00 to 70.81) in the absolute value groups. [CI, confidence interval]

8.1.3.3. Accuracy outcomes – RMS deviations

Three articles reported the RMS deviations of the implant analogs[35, 40, 41] and two more studies reported “3D deviations”[37, 39], which were similar to RMS but could not be pooled together because the number of measurements was not reported in some articles. Figures 6 and 7 show the RMS values of the control and intervention groups, respectively. The overall mean RMS for the intervention group was $95.01 \mu\text{m}$ [95% CI, 66.96 - 123.05]. The control group showed an overall deviation of $80.39 \mu\text{m}$ [95% CI, 15.43 ; 145.35]. Figure 8 shows the mean difference in the RMS deviations between the

two groups. The overall difference between the RMS values was 14.74 μm [95% CI, -107.26 to 136.74].

Figure 6 Forest plot of root mean square (RMS) deviations of implant analogs (μm) in the control group. The pooled mean deviation was 80.39 (95% CI: 15.43 to 145.35). [CI, confidence interval]

Figure 7 Forest plot of root mean square (RMS) deviations of implant analogs (μm) in the intervention group. The pooled mean deviation was 95.01 (95% CI: 66.96 to 123.05). [CI, confidence interval]

Figure 8 Forest plot of mean difference of root mean square (RMS) deviations of the control and intervention groups (μm). The pooled mean difference was 14.74 (95% CI:

-107.26 to 136.74). [CI, confidence interval]

8.1.4. Risk of bias assessment

After all eligible studies were evaluated using the 12-item checklist of the QUIN tool, they were judged to have a low, medium, or high RoB. Four studies were rated as having “some concerns”[34, 36, 37, 39], mainly because of the absence of sample size calculation and lack of specification of the number and training of operators and assessors. Four studies were rated as “low risk”[35, 38, 40, 41], and no study was excluded due to a high RoB.

8.1.5. Outcome assessment

The accuracy outcomes were assessed by measuring the deviation of the implant analogs in the reference and test models. In three articles, the center of the implant analogs was measured directly using a coordinate-measuring machine (CMM)[36, 37, 39]. In five articles, the definitive models were scanned with scanbodies attached to the analogs, and the deviations were measured by superimposing the Standard Tessellation Files[34, 35, 38, 40, 41].

8.2. Study II - Accuracy of Digital and Conventional Implant Impressions in Edentulous Jaws: A Systematic Review and Meta-Analysis of In Vitro Studies

8.2.1. Study selection

Initially, the systematic search identified 4,585 articles. Following the duplicate removal, 2,588 records remained for screening. Based on the title and abstract, 174 publications were selected for full-text review. Of these, 140 were excluded according to the predefined eligibility criteria. Ultimately, 34 studies met the inclusion criteria and were included in the systematic review and the meta-analysis. The inter-rater agreement was measured by Cohen's kappa and yielded 0.89 for title- and abstract screening, and 1 for full-text assessment.

Figure 9 PRISMA flowchart of the study selection process for the systematic review in Study II, showing the number of records identified, screened, excluded, and included.

8.2.2. Study characteristics

The included articles were in vitro interventional studies using experimental gypsum or resin models as reference. The reference model contained four implants in 16

cases[42-57], five implants in four instances[58-61], six implants in 12 cases[62-73], and eight implants in two cases[74, 75]. The implants were parallel to each other in 17 cases[43, 44, 47-49, 53, 54, 56-58, 63, 67, 69-71, 73, 74], angulated in 16 instances[42-47, 50, 52, 55, 58-60, 62, 64, 72, 75], and it was not disclosed in five cases.[51, 61, 65, 66, 68] In four articles, models with both angulated and parallel implants were examined.[43, 44, 47, 58] Additional characteristics, such as angulation of the implants, level of impression-taking, method of impression-taking, and so on, were too heterogeneous to create subgroups. Still, they are included in the plots as “comments”.

For reference scanning, 27 articles used laboratory-grade desktop scanners, three studies used industrial-grade scanners, and five studies used a coordinate measuring machine.

8.2.3. Outcome assessment

The accuracy outcomes were assessed by measuring the surface of the models or the implant analogs in the reference and test models. The articles mentioned three methods: a coordinate measuring machine (CMM), a laboratory-grade desktop scanner, or an industrial-grade scanner. The definitive models were scanned with scanbodies attached to the analogs, and the deviations were measured by superimposing the reference and test standard tessellation language (STL) files.

8.2.4. Results of the synthesis

8.2.4.1. Accuracy outcomes – RMS trueness

The root-mean-square (RMS) trueness deviations of the models were reported overall across 18 studies. The means and standard deviations were pooled by acquisition method as follows: *extraoral stereophotogrammetry*, *conventional impression*, *IOS plain*, *IOS scanaid*, and *IOS splinted*.

Figure 10 shows the RMS trueness values for the interventions, grouped by method. *Extraoral stereophotogrammetry* showed an overall mean of 53.36 μm with a 95% confidence interval of [18.44; 88.28], *conventional impression* showed an overall mean of 73.88 μm [36.68; 111.09], *IOS plain* showed an overall mean of 99.54 μm [56.22;

142.86], *IOS scanaid* showed an overall mean of 104.88 μm [36.86; 172.9] and *IOS splinted* showed an overall mean of 65.58 μm [5.24; 125.92]. Figure 11 shows the summed results for each subgroup, providing a more straightforward, visual view.

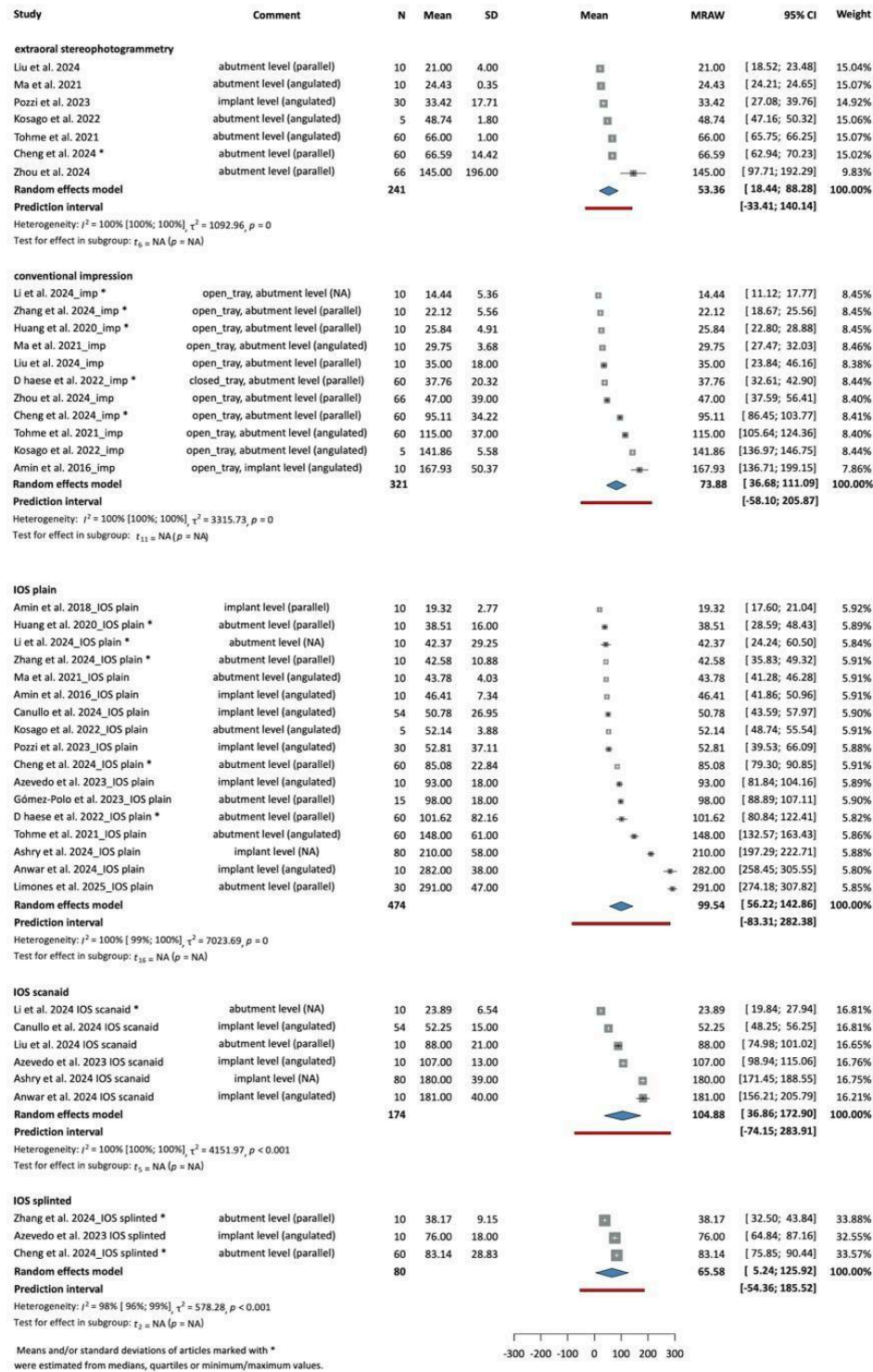


Figure 10 Forest plot of the RMS trueness deviations (μm)

measured in the tested groups subgrouped by the impression-taking method. [CI, confidence interval]

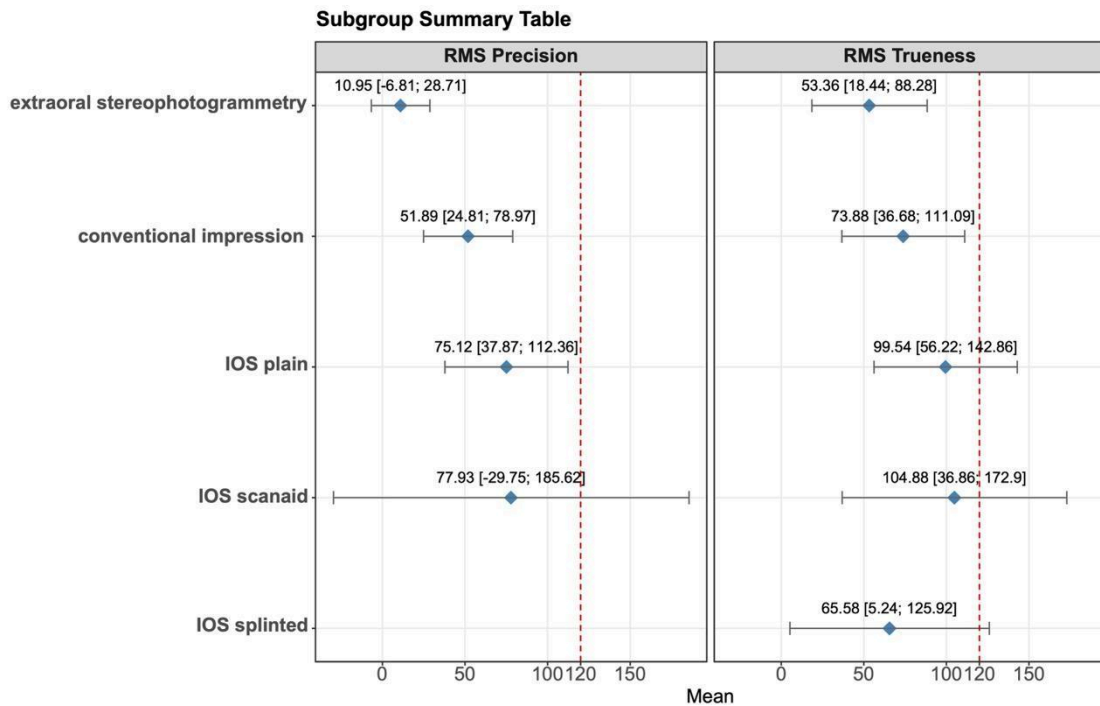


Figure 11 Pooled summary of root mean square (RMS) trueness and precision deviations (μm) grouped and summed by impression-taking method. Precision of the “IOS splinted” group is omitted from the figure because of the low number of studies.

8.2.4.2. Accuracy outcomes – RMS precision

The root-mean-square (RMS) precision deviations of the models were reported across 12 studies. The means and standard deviations were pooled by acquisition method as follows: *extraoral stereophotogrammetry*, *conventional impression*, *IOS plain*, *IOS scanaid*, and *IOS splinted*. In the IOS splinted category, only two articles were included, so no random-effects model was calculated; however, the studies are included in the figure to illustrate the trend.

Figure 12 shows the RMS precision values of the interventions, grouped by method. *Extraoral stereophotogrammetry* showed an overall mean of 10.95 μm [-6.81; 28.71], *conventional impression* showed an overall mean of 51.89 μm [24.81; 78.97], *IOS plain*

showed an overall mean of 75.12 μm [37.87; 122.36], and *IOS scanaid* showed an overall mean of 77.93 μm [-29.75; 185.62]. Figure 11 shows the summed results for each subgroup, providing a more straightforward, visual view.

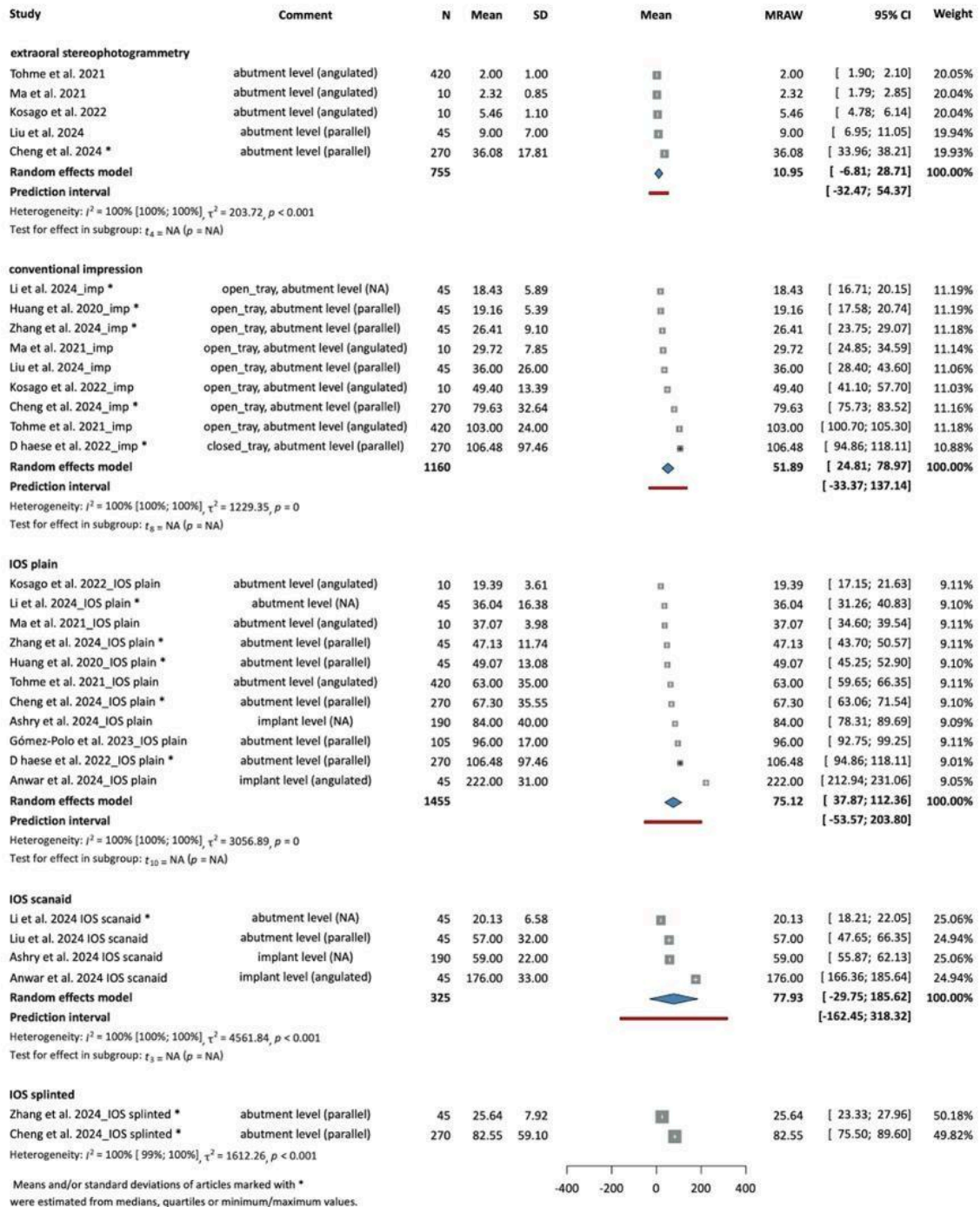


Figure 12 Forest plot of the root mean square (RMS) precision deviations measured in the tested groups subgrouped by the impression-taking method (μm). [CI, confidence interval]

8.2.5. Risk of bias assessment

All included articles were assessed for risk of bias (RoB) using the 12-item checklist of QUIN RoB tool [32], and categorized as having low, moderate, or high RoB. 22 studies were categorized as “some concerns” and 12 studies were judged to present “low risk” of bias. In most cases, the distinction between low and medium risk was due to missing or inaccurate sample size calculations and a lack of detail regarding the number and experience of operators and assessors. No studies were excluded based on a high RoB rating.

9. DISCUSSION

9.1. Summary of findings, international comparisons

The aim of study I was to evaluate the accuracy of definitive implant casts produced using additive and conventional technologies, based on evidence from in vitro studies. We hypothesized that additive manufacturing techniques used in implant prosthodontics would yield lower accuracy than traditional gypsum cast-fabrication methods. However, our findings revealed no statistically significant or clinically meaningful differences between the two approaches, indicating that the initial hypothesis of additive technologies' inferior accuracy was not supported.

At present, there is no universally accepted standard for clinically acceptable dental model accuracy. Nonetheless, several accuracy ranges have been proposed depending on the intended application of the casts[76]. For diagnostic, treatment-planning, or educational purposes, deviations of up to 300–500 μm are considered acceptable[12, 13]. In orthodontic applications, such as aligner fabrication, Kim et al., Wesseman et al., and Akyalcin et al. recommended limiting deviations to ≤ 250 μm [12, 14, 15]. Prosthodontic applications require stricter accuracy standards, particularly for implant-supported restorations. Screw-retained implant prostheses demand a high level of precision, as inaccuracies in implant analog positioning may prevent proper prosthesis seating and compromise occlusal and interproximal contacts. Printed casts are frequently used for adjusting occlusal and interdental contacts, as well as for individualized staining, finishing, and polishing of prostheses[16, 77]. Each step in the prosthodontic workflow may introduce deviations that contribute to the final misfit of the restoration. Positional deviations encompass inaccuracies arising during both digital and conventional impression-taking and cast-fabrication processes. Variations in these procedures between the two methods may also influence accuracy. Notably, the included studies did not provide sufficient data to distinguish inaccuracies introduced at individual workflow stages.

To identify small mean deviations that could be masked by the cancellation of large positive and negative values, an analysis of mean absolute deviation was additionally performed. The pooled mean absolute deviation reflected the overall reliability of the methods and the average magnitude of errors, irrespective of their direction.

When evaluating the accuracy of printed casts, prosthetic accuracy parameters represent appropriate reference values. Historically, an acceptance threshold of 120 μm was established based on the findings of McLean et al.[78]. However, advances in digital dentistry and modern prosthodontic workflows have substantially surpassed this benchmark. Schwindling et al. reported misfit values ranging from 36 to 88 μm for monolithic full arch restorations produced using a digital workflow in an in vitro setting[77]. Similarly, Lyu et al. demonstrated that monolithic zirconia crowns fabricated by nanoparticle jetting exhibited RMS deviations as low as 22.9 μm [79]. When assessed against the traditionally cited 120 μm threshold, the present findings may appear clinically negligible.

In contrast, considering more recent evidence [77, 79], the results may indeed hold clinical relevance. It should be emphasized, however, that these findings are derived from individual studies and that no widely accepted clinical guidelines currently exist. Establishing a clear accuracy threshold is essential for evaluating the consequences of implant restoration misfit. Katsoulis et al. found insufficient evidence linking misfit to biological or mechanical complications in screw-retained, implant-supported fixed prostheses, although screw-related mechanical issues were reported in some cases [80]. The extent of acceptable misfit remains uncertain. More recent investigations suggest that mechanical implications may be more critical than biological ones. Abdelrehim et al. reported a relatively wide range of tolerable misfit values but still did not define a universal threshold for clinical acceptability. Their findings indicated that horizontal and vertical misfits of up to 150 μm did not result in mechanical complications, while biological tolerance extended to misfits as large as 1 mm [81]. Considering these data, the clinical relevance of the differences observed between conventional and additive cast-fabrication methods appears diminished, further supporting the conclusion that additive manufacturing represents a reliable alternative.

All studies included in this review were conducted in vitro, which limits their direct clinical applicability. One major challenge in performing in vivo research is the lack of a standardized, well-defined protocol for evaluating the accuracy of impression-taking and cast-fabrication. Additionally, clinical factors such as saliva, temperature, and material handling may influence the accuracy of outcomes. In vitro studies offer the advantage of controlled conditions and standardized methodologies. The included

studies employed digital measurement techniques to quantify deviations between reference and test models, providing precise numerical data.

In contrast, *in vivo* studies often rely on clinical indicators such as passive fit. The present analysis demonstrated relatively large standard deviations and wide confidence intervals, which may be attributable to differences in impression techniques, cast-fabrication methods, measurement technologies, data analysis, and reporting practices. Variations in scan bodies and implant analog designs may also contribute to these discrepancies, although insufficient data prevent definitive conclusions [37].

Several studies compared direct digital workflows using intraoral scanning with conventional impression-taking and cast-fabrication methods [35, 38, 40, 41], whereas others utilized laboratory scanners to generate digital models [34, 36, 37, 39]. Borbola et al. reported superior overall accuracy for laboratory scanners compared with intraoral scanners [82]. Nevertheless, the present analysis did not demonstrate a clear association between the applied scanning method and accuracy outcomes.

To enable comparison between methods, both test and reference models were digitized. Coordinate measuring machines were employed in three studies [36, 37, 39], laboratory optical scanners in three studies [34, 38, 40], and intraoral scanners in two studies [35, 41]. Although this digitization step may introduce additional distortions, such effects were not evident in the reported results.

The study populations were heterogeneous, ranging from single-implant cases to full arch restorations. Previous research has shown that intraoral scanners exhibit reduced accuracy over longer scanning distances due to cumulative errors [83], and edentulous arches pose particular challenges for accurate scanning [84]. Furthermore, software updates and scanner versions have been shown to significantly influence the trueness and precision of intraoral scanning systems [85].

In study II we hypothesized that digital impression-taking techniques, including intraoral scanning and extraoral stereophotogrammetry, would demonstrate lower accuracy than the gold-standard conventional impression method. The results revealed no statistically significant differences among the evaluated techniques, indicating that the initial hypothesis regarding the inferior accuracy of digital impression-taking technologies was not supported.

Historically, most intraoral scanners were not recommended for full arch applications, and it remains uncertain whether they can consistently achieve the level of accuracy required for full arch restorations. This concern is particularly relevant in cases of complete edentulism and implant restorations with large interimplant distances. Intraoral scanners generate a three-dimensional mesh by stitching together multiple images based on overlapping regions and common reference points. Surfaces with greater anatomical detail provide more stable reference points for this process; for example, the occlusal surfaces of premolars and molars facilitate accurate image alignment. In contrast, extensive edentulous areas lack such reference features, making the stitching process more challenging. Scanning is especially demanding in fully edentulous mandibular arches, where mucosal mobility further compromises image acquisition.

As discussed for Study I, no universally accepted accuracy threshold currently exists for dental models or implant-supported prostheses, and the interpretation below is therefore made against the commonly cited 120 μm benchmark introduced earlier.

If the commonly cited 120 μm threshold is accepted as the criterion for clinical acceptability, deviations below this value may be considered acceptable. From this perspective, all impression-taking methods evaluated in the present study can be regarded as clinically acceptable. Mean trueness deviations ranged from 53.36 μm (18.44; 88.28) to 104.88 μm (36.86; 172.90), while mean precision deviations varied between 10.95 μm (−6.81; 28.71) and 77.93 μm (−29.75; 185.62). Nevertheless, it is important to highlight that the difference between the most accurate method (extraoral stereophotogrammetry) and the least accurate method (IOS scanaid) was nearly twofold.

To address the challenges associated with full arch, particularly edentulous, scanning and to reduce inaccuracies, several novel scanning methods and auxiliary devices have been introduced. One such approach involves splinting scanbodies in a manner analogous to conventional impression copings, using materials such as dental floss, self-curing resin, or prefabricated splints. In conventional impression-taking, splinting serves a mechanical function by stabilizing impression copings within a rigid framework, preventing movement. In the context of intraoral scanning, splinting provides additional reference points between scanbodies, thereby facilitating the stitching process in edentulous regions. The use of splinted scanbodies resulted in substantially improved trueness and precision compared with “plain” intraoral scanning, defined as scanning without splinting or additional aids. However, this finding should be interpreted with caution, as the splinted scanbody subgroup included only three studies for trueness and two for precision outcomes.

In contrast, studies classified under the “scanaid” subgroup employed various strategies to compensate for scanning inaccuracies, including elongated scan flags, prefabricated scanbody attachments, customized scanbodies, and geometric attachments placed on the mucosa. When pooled, these approaches did not improve intraoral scanning accuracy and, in fact, produced slightly inferior results compared with plain scanning. Nonetheless, the observed differences were minimal, amounting to 5.34 μm in trueness and 2.81 μm in precision. The limited number of studies in this subgroup represents a notable limitation.

Extraoral stereophotogrammetry systems are recognized for their high accuracy, a finding corroborated by the present analysis, which demonstrated superior trueness and precision values compared with other methods. Despite their accuracy, these systems have notable drawbacks: they are expensive, limited to a specific application, and still require an intraoral scanner to capture soft-tissue morphology. Additionally, all scanbodies must be visible simultaneously, which can be challenging in patients with unfavorable anatomy or restricted mouth opening.

The present analysis revealed discernible differences in accuracy between conventional and various digital implant impression-taking techniques. Although these differences did not reach statistical significance, potential clinical implications cannot be entirely

excluded. A definitive accuracy threshold could be established by evaluating the clinical consequences of implant restoration misfit in relation to the magnitude of deviation.

All studies included in this analysis were performed *in vitro*, which limits the direct clinical applicability of the findings. Clinical variables such as saliva, temperature, material handling, and ambient lighting may influence impression-taking accuracy under *in vivo* conditions.

The included studies assessed deviations using digital measurement techniques, thereby enabling precise numerical reporting and facilitating statistical analysis. In contrast, *in vivo* investigations often rely on clinical indicators such as passive fit or radiographic evaluation. The analyses demonstrated substantial heterogeneity, likely attributable to differences among the included studies in terms of methodology, data processing, and reporting practices.

9.2. Strengths

Both studies included in this thesis address clinically relevant and timely topics related to the accuracy of digital workflows in implant dentistry. Both studies were conducted using strict, prospectively registered methodological protocols, and the results were reported consistently and transparently. A key strength of both articles is the use of statistical analysis, which distinguishes them from several previous reviews in this field. Furthermore, the inclusion of a high number of studies in study II, incorporating some of the most recent digital and conventional methods, enhances the RoBustness of the analyses and increases the clinical relevance of the findings.

9.3. Limitations

A major constraint in both studies was the heterogeneity of the included *in vitro* studies, particularly with respect to the conventional and digital impression-taking techniques, reference data acquisition, cast-fabrication procedures, and measurement methods. Variations in scanners, materials, 3D printers, and measurement technologies represented important confounding factors that could not be fully accounted for due to the complexity of these systems and the limited availability of detailed data. In addition,

the overall number of eligible studies in study I was limited, which restricted the amount of data available for analysis. The exclusive inclusion of in vitro studies further limits the direct clinical applicability of the findings. Moreover, concerns about risk of bias were identified in several included studies, most commonly due to the absence of sample size calculations. Finally, shortcomings in data reporting and transparency were noted in several articles, which may affect the reliability and interpretability of the results.

10. CONCLUSIONS

1. Additively manufactured implant models were as accurate as conventional gypsum models. Our findings suggest that additive cast-fabrication is a viable alternative to conventional methods in implant prosthodontics.
2. Intraoral scanning and extraoral stereophotogrammetry are suitable alternatives to impression-taking for completely edentulous lower jaws restored with four to eight implants. Extraoral stereophotogrammetry showed the most favorable trueness and precision point estimates, though differences did not reach statistical significance.

11. IMPLICATIONS FOR PRACTICE

Although Study I is based on in vitro data and has clinical limitations, it provides precise and reliable data and currently has the highest evidence level on the topic. The accuracy results of Study I should encourage clinicians to use additive cast-fabrication technologies. The choice between the two methods should be based on additional clinical parameters, case requirements, and patient preference.

Study II provides clinically relevant evidence on the accuracy of conventional and digital impression techniques for “All-on-X” treatments in edentulous jaws. This data supports informed decision-making in implant-supported prosthetic rehabilitation and demonstrates that all methods are clinically acceptable, while certain digital methods offer superior precision.

12. IMPLICATIONS FOR RESEARCH

Further research is necessary to determine and establish clinically acceptable accuracy thresholds to provide context and relevance for future studies of accuracy.

A standardized form of reporting throughout accuracy data would greatly increase the scientific value of further investigations.

For enhanced clinical and scientific value, both linear and 3D deviations should be measured and reported as signed values whenever possible.

13. IMPLICATIONS FOR POLICYMAKERS

The available evidence suggests that additive cast-fabrication and digital impression techniques, including extraoral stereophotogrammetry, may achieve accuracy comparable to conventional workflows in implant prosthodontics. These findings may support their consideration in future clinical guidelines and coverage frameworks, although the current evidence base remains insufficient for strong or definitive recommendations. In addition, the lack of universally accepted accuracy thresholds and standardized reporting methods highlights the need for further research and coordinated efforts to establish clinically meaningful benchmarks.

14. FUTURE PERSPECTIVES

Among the numerous possibilities, a well-described, evidence-based protocol would be necessary for implant-supported prostheses to achieve the best possible accuracy. With these two studies investigating the accuracy of additive cast-fabrication and digital impression-taking, we are one step closer to this goal.

Currently, we are broadening our scope by conducting in vitro research in cooperation with the UTHealth Houston School of Dentistry, focusing on the accuracy of intra- and extraoral stereophotogrammetry systems.

For even greater clinical relevance and practical application, we plan to start in vivo research, including full arch implant cases.

15. REFERENCES

1. Pachiou A, Zervou E, Sykaras N, Tortopidis D, Ioannidis A, Jung RE, et al. Patient-Reported Outcomes of Digital Versus Conventional Impressions for Implant-Supported Fixed Dental Prostheses: A Systematic Review and Meta-Analysis. *J Pers Med*. 2025;15(9).
2. Ramos-Morro OD, Mareque-Ameijeiras S, Giovannini G, Paz-Cortés MM, Serrano-Velasco D, Aragonese JMM, et al. Evaluation of the patient's perception, reliability and reproducibility, and chairside time with intraoral scanners in adult population—a systematic review. *Frontiers in Oral Health*. 2026;Volume 7 - 2026.
3. Vánkos B, Qian X, Kelemen K, Mikulás K, Kói T, Tóth R, et al. Accuracy of conventional versus additive cast-fabrication in implant prosthodontics: A systematic review and meta-analysis of in vitro studies. *J Prosthodont Res*. 2025;69(2):163-72.
4. Vánkos BL, Qian X, Kelemen K, Szentes BL, Agócs G, Varga G, et al. Accuracy of Digital and Conventional Implant Impressions in Edentulous Jaws: A Systematic Review and Meta-Analysis of In Vitro Studies. *Dentistry Journal*. 2026;14(5):304.
5. Mangano F, Gandolfi A, Luongo G, Logozzo S. Intraoral scanners in dentistry: a review of the current literature. *BMC Oral Health*. 2017;17(1):149.
6. Veroniki AA, Jackson D, Viechtbauer W, Bender R, Bowden J, Knapp G, et al. Methods to estimate the between-study variance and its uncertainty in meta-analysis. *Res Synth Methods*. 2016;7(1):55-79.
7. Giménez B, Özcan M, Martínez-Rus F, Pradíes G. Accuracy of a digital impression system based on active wavefront sampling technology for implants considering operator experience, implant angulation, and depth. *Clin Implant Dent Relat Res*. 2015;17 Suppl 1:e54-64.
8. Alsharbaty MHM, Alikhasi M, Zarrati S, Shamshiri AR. A Clinical Comparative Study of 3-Dimensional Accuracy between Digital and Conventional Implant Impression Techniques. *J Prosthodont*. 2019;28(4):e902-e8.

9. Schmidt A, Wöstmann B, Schlenz MA. Accuracy of digital implant impressions in clinical studies: A systematic review. *Clin Oral Implants Res.* 2022;33(6):573-85.
10. Jain S, Daak HA, Someli LA, Alamer AY, Apratim A, Akoor RMA, et al. Accuracy of Stereophotogrammetry Technique versus Intraoral Scanners for Complete-Arch Implant Digital Impressions: A Systematic Review and Meta-Analysis. *Eur J Dent.* 2026;20(1):34-48.
11. Arcuri L, Pozzi A, Londono J, Nardi A, Testarelli L, Galli M. Complete arch digital implant scan accuracy with screw-retained or snap-on scan bodies: A comparative in vitro study. *J Prosthet Dent.* 2025;134(3):774-81.
12. Wesemann C, Muallah J, Mah J, Bumann A. Accuracy and efficiency of full arch digitalization and 3D printing: A comparison between desktop model scanners, an intraoral scanner, a CBCT model scan, and stereolithographic 3D printing. *Quintessence Int.* 2017;48(1):41-50.
13. Wan Hassan WN, Yusoff Y, Mardi NA. Comparison of reconstructed rapid prototyping models produced by 3-dimensional printing and conventional stone models with different degrees of crowding. *Am J Orthod Dentofacial Orthop.* 2017;151(1):209-18.
14. Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. *Am J Orthod Dentofacial Orthop.* 2018;153(1):144-53.
15. Tsolakis IA, Gizani S, Panayi N, Antonopoulos G, Tsolakis AI. Three-Dimensional Printing Technology in Orthodontics for Dental Models: A Systematic Review. *Children (Basel).* 2022;9(8).
16. Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. *Br Dent J.* 2015;219(11):521-9.
17. Ma Y, Al-Radhi RYZ, Jiang L, Yu H. Does Splinting the Direct Copings Increase the Impression Accuracy of Two-Unit Nonparallel Implant Restorations? A Systematic Review and Meta-analysis. *Int J Oral Maxillofac Implants.*

2022;37(4):653-9.

18. Shetty PS, Gangurde AP, Chauhan MR, Jaiswal NV, Salián PR, Singh V. Accuracy of the digital implant impression with splinted and non-splinted intraoral scan bodies: A systematic review. *J Indian Prosthodont Soc.* 2025;25(1):3-12.
19. Khan SA, Tushar, Nezam S, Singh P, Kumari N, Singh SS. Comparison and Evaluation of Linear Dimensional Accuracy of Three Elastomeric Impression Materials at Different Time Intervals Using Vision Inspection System: An In Vitro Study. *J Int Soc Prev Community Dent.* 2020;10(6):736-42.
20. Lee SJ, Betensky RA, Gianneschi GE, Gallucci GO. Accuracy of digital versus conventional implant impressions. *Clin Oral Implants Res.* 2015;26(6):715-9.
21. Gehrke P, Rashidpour M, Sader R, Weigl P. A systematic review of factors impacting intraoral scanning accuracy in implant dentistry with emphasis on scan bodies. *Int J Implant Dent.* 2024;10(1):20.
22. Singh R, Mistry G, Kini A, Ansari R, Kailaje V, Kapoor S. Accuracy and Clinical Performance of Intraoral Scanners Compared to Conventional and Extraoral Impressions: An Umbrella Review. *Cureus.* 2025;17(9):e93202.
23. Pozzi A, Arcuri L, Carosi P, Laureti A, Londono J, Wang HL. Photogrammetry Versus Intraoral Scanning in Complete-Arch Digital Implant Impression: A Systematic Review and Meta-Analysis. *Clin Implant Dent Relat Res.* 2025;27(3):e70059.
24. Higgins JPT TJ, Chandler J, Cumpston M, Li T, Page MJ, et al., editor. *Cochrane Handbook for Systematic Reviews of Interventions.* version 6.5 (updated August 2024) ed2024.
25. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ.* 2021;372:n71.
26. Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan—a web and mobile app for systematic reviews. *Systematic Reviews.* 2016;5(1):210.

27. Harrer M, Cuijpers P, Furukawa T, Ebert D. Doing Meta-Analysis with R: A Hands-On Guide 2021.
28. Pustejovsky JE, Tipton E. Meta-analysis with RoBust Variance Estimation: Expanding the Range of Working Models. *Prev Sci.* 2022;23(3):425-38.
29. Luo D, Wan X, Liu J, Tong T. Optimally estimating the sample mean from the sample size, median, mid-range, and/or mid-quartile range. *Stat Methods Med Res.* 2018;27(6):1785-805.
30. Wan X, Wang W, Liu J, Tong T. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. *BMC Med Res Methodol.* 2014;14:135.
31. Rohatgi A. WebPlotDigitizer [Available from: <https://automeris.io>].
32. Sheth VH, Shah NP, Jain R, Bhanushali N, Bhatnagar V. Development and validation of a risk-of-bias tool for assessing in vitro studies conducted in dentistry: The QUIN. *J Prosthet Dent.* 2024;131(6):1038-42.
33. Schünemann H BJ, Guyatt G, Oxman A. Handbook for grading the quality of evidence and the strength of recommendations using the GRADE approach.
34. Buda M, Bratos M, Sorensen JA. Accuracy of 3-dimensional computer-aided manufactured single-tooth implant definitive casts. *J Prosthet Dent.* 2018;120(6):913-8.
35. Banjar A, Chen YW, Kostagianni A, Finkelman M, Papathanasiou A, Chochlidakis K, et al. Accuracy of 3D Printed Implant Casts Versus Stone Casts: A Comparative Study in the Anterior Maxilla. *J Prosthodont.* 2021;30(9):783-8.
36. Olea-Vielba M, Jareño-García D, Methani MM, Martinez-Klemm I, Revilla-León M. Accuracy of the Implant Replica Positions on the Complete Edentulous Additive Manufactured Cast. *J Prosthodont.* 2020;29(9):780-6.
37. Revilla-León M, Fogarty R, Barrington JJ, Zandinejad A, Özcan M. Influence of scan body design and digital implant analogs on implant replica position in additively

manufactured casts. J Prosthet Dent. 2020;124(2):202-10.

38. Mata-Mata SJ, Donmez MB, Meirelles L, Johnston WM, Yilmaz B. Influence of digital implant analog design on the positional trueness of an analog in additively manufactured models: An in-vitro study. Clin Implant Dent Relat Res. 2022;24(6):821-30.

39. Revilla-León M, Gonzalez-Martín Ó, Pérez López J, Sánchez-Rubio JL, Özcan M. Position Accuracy of Implant Analogs on 3D Printed Polymer versus Conventional Dental Stone Casts Measured Using a Coordinate Measuring Machine. J Prosthodont. 2018;27(6):560-7.

40. Alshawaf B, Weber HP, Finkelman M, El Rafie K, Kudara Y, Papaspyridakos P. Accuracy of printed casts generated from digital implant impressions versus stone casts from conventional implant impressions: A comparative in vitro study. Clin Oral Implants Res. 2018;29(8):835-42.

41. Abdeen L, Chen YW, Kostagianni A, Finkelman M, Papathanasiou A, Chochlidakis K, et al. Prosthesis accuracy of fit on 3D-printed casts versus stone casts: A comparative study in the anterior maxilla. J Esthet Restor Dent. 2022;34(8):1238-46.

42. Pozzi A, Carosi P, Gallucci GO, Nagy K, Nardi A, Arcuri L. Accuracy of complete-arch digital implant impression with intraoral optical scanning and stereophotogrammetry: An in vivo prospective comparative study. Clin Oral Implants Res. 2023;34(10):1106-17.

43. Alikhasi M, Siadat H, Nasirpour A, Hasanzade M. Three-Dimensional Accuracy of Digital Impression versus Conventional Method: Effect of Implant Angulation and Connection Type. Int J Dent. 2018;2018:3761750.

44. Gómez-Polo M, Cascos R, Ortega R, Barmak AB, Kois JC, Revilla-León M. Influence of arch location and scanning pattern on the scanning accuracy, scanning time, and number of photograms of complete-arch intraoral digital implant scans. Clin Oral Implants Res. 2023;34(6):591-601.

45. Shaikh M, Lakha T, Kheur S, Qamri B, Kheur M. Do digital impressions have a

greater accuracy for full arch implant-supported reconstructions compared to conventional impressions? An in vitro study. *J Indian Prosthodont Soc.* 2022;22(4):398-404.

46. Tohme H, Lawand G, Eid R, Ahmed KE, Salameh Z, Makzoume J. Accuracy of Implant Level Intraoral Scanning and Photogrammetry Impression Techniques in a Complete Arch with Angled and Parallel Implants: An In Vitro Study. *Applied Sciences.* 2021;11(21):9859.

47. Ribeiro P, Herrero-Climent M, Díaz-Castro C, Ríos-Santos JV, Padrós R, Mur JG, et al. Accuracy of Implant Casts Generated with Conventional and Digital Impressions—An In Vitro Study. *International Journal of Environmental Research and Public Health.* 2018;15(8):1599.

48. Ke Y, Zhang Y, Wang Y, Chen H, Sun Y. Comparing the accuracy of full arch implant impressions using the conventional technique and digital scans with and without prefabricated landmarks in the mandible: An in vitro study. *J Dent.* 2023;135:104561.

49. Huang R, Liu Y, Huang B, Zhang C, Chen Z, Li Z. Improved scanning accuracy with newly designed scan bodies: An in vitro study comparing digital versus conventional impression techniques for complete-arch implant rehabilitation. *Clin Oral Implants Res.* 2020;31(7):625-33.

50. Anwar H, Azer A, AboElHassan RG. Influence of a specially designed geometric device and modified scan bodies on the accuracy of a maxillary complete arch digital implant scan: An in vitro study. *J Prosthet Dent.* 2024;131(4):683.e1-e7.

51. Ashry A, Abdelhamid AM, Ezzelarab S, Khamis MM. Effect of using scan body accessories and inter-implant distances on the accuracy of complete arch implant digital impressions: An in vitro study. *J Prosthodont.* 2025;34(8):827-35.

52. Canullo L, Pesce P, Caponio VCA, Iacono R, Luciani FS, Raffone C, et al. Effect of auxiliary geometric devices on the accuracy of intraoral scans in full arch implant-supported rehabilitations: An in vitro study. *J Dent.* 2024;145:104979.

53. Zhang T, Yang B, Ge R, Zhang C, Zhang H, Wang Y. Effect of a Novel 'Scan Body' on the In Vitro Scanning Accuracy of Full arch Implant Impressions. *Int Dent J*. 2024;74(4):847-54.
54. Limones A, Çakmak G, Fonseca M, Roccuzzo A, Cobo-Vázquez C, Gómez-Polo M, et al. Impact of scanning interruptions on accuracy of implant-supported full arch scans: An in-vitro pilot study. *J Dent*. 2025;153:105503.
55. Pera F, Pesce P, Bevilacqua M, Setti P, Menini M. Analysis of Different Impression Techniques and Materials on Multiple Implants Through 3-Dimensional Laser Scanner. *Implant Dent*. 2016;25(2):232-7.
56. Asli HN, Hemmati YB, Falahchai M. Three-dimensional accuracy of innovative implant-level impression techniques with plastic snap-on impression copings. *Dent Med PResBl*. 2021;58(3):351-7.
57. Wu HK, Chen G, Zhang Z, Lin X, Huang X, Deng F, et al. Effect of artificial landmarks of the prefabricated auxiliary devices located at different arch positions on the accuracy of complete-arch edentulous digital implant scanning: An in-vitro study. *J Dent*. 2024;140:104802.
58. Amin S, Weber HP, Finkelman M, El Rafie K, Kudara Y, Papaspyridakos P. Digital vs. conventional full arch implant impressions: a comparative study. *Clin Oral Implants Res*. 2017;28(11):1360-7.
59. Kosago P, Ungurawasaporn C, Kukiattrakoon B. Comparison of the accuracy between conventional and various digital implant impressions for an implant-supported mandibular complete arch-fixed prosthesis: An in vitro study. *J Prosthodont*. 2023;32(7):616-24.
60. Papaspyridakos P, Gallucci GO, Chen CJ, Hanssen S, Naert I, Vandenberghe B. Digital versus conventional implant impressions for edentulous patients: accuracy outcomes. *Clin Oral Implants Res*. 2016;27(4):465-72.
61. Drancourt N, Auduc C, Mouget A, Mouminoux J, Auroy P, Veyrune JL, et al. Accuracy of Conventional and Digital Impressions for Full arch Implant-Supported

Prostheses: An In Vitro Study. *J Pers Med.* 2023;13(5).

62. Ma B, Yue X, Sun Y, Peng L, Geng W. Accuracy of photogrammetry, intraoral scanning, and conventional impression techniques for complete-arch implant rehabilitation: an in vitro comparative study. *BMC Oral Health.* 2021;21(1):636.
63. D'Haese R, Vrombaut T, Roeykens H, Vandeweghe S. In Vitro Accuracy of Digital and Conventional Impressions for Full arch Implant-Supported Prostheses. *J Clin Med.* 2022;11(3).
64. Kim KR, Seo KY, Kim S. Conventional open-tray impression versus intraoral digital scan for implant-level complete-arch impression. *J Prosthet Dent.* 2019;122(6):543-9.
65. Revilla-León M, Rubenstein J, Methani MM, Piedra-Cascón W, Özcan M, Att W. Trueness and precision of complete-arch photogrammetry implant scanning assessed with a coordinate-measuring machine. *J Prosthet Dent.* 2023;129(1):160-5.
66. Tan MY, Yee SHX, Wong KM, Tan YH, Tan KBC. Comparison of Three-Dimensional Accuracy of Digital and Conventional Implant Impressions: Effect of Interimplant Distance in an Edentulous Arch. *Int J Oral Maxillofac Implants.* 2019;34(2):366–80.
67. Cheng J, Zhang H, Liu H, Li J, Wang HL, Tao X. Accuracy of edentulous full arch implant impression: An in vitro comparison between conventional impression, intraoral scan with and without splinting, and photogrammetry. *Clin Oral Implants Res.* 2024;35(5):560-72.
68. Li Y, Fang H, Yan Y, Geng W. Accuracy of intraoral scanning using modified scan bodies for complete arch implant-supported fixed prostheses. *J Prosthet Dent.* 2024;132(5):994.e1-.e8.
69. Zhou Y, You L, Fan Z. Accuracy of implant abutment level digital impressions using stereophotogrammetry in edentulous jaws: an in vitro pilot study. *BMC Oral Health.* 2024;24(1):1167.

70. Liu M, Fu XJ, Lai HC, Shi JY, Liu BL. Accuracy of traditional open-tray impression, stereophotogrammetry, and intraoral scanning with prefabricated aids for implant-supported complete arch prostheses with different implant distributions: An in vitro study. *J Prosthet Dent.* 2024;132(3):602.e1-.e9.
71. Gómez-Polo M, Sallorenzo A, Cascos R, Ballesteros J, Barmak AB, Revilla-León M. Conventional and digital complete arch implant impression techniques: An in vitro study comparing accuracy. *J Prosthet Dent.* 2024;132(4):809-18.
72. Azevedo L, Marques T, Karasan D, Fehmer V, Sailer I, Correia A, et al. Effect of splinting scan bodies on the trueness of complete arch digital implant scans with 5 different intraoral scanners. *J Prosthet Dent.* 2024;132(1):204-10.
73. Vandeweghe S, Vervack V, Dierens M, De Bruyn H. Accuracy of digital impressions of multiple dental implants: an in vitro study. *Clin Oral Implants Res.* 2017;28(6):648-53.
74. Rajendran R, Chander NG, Anitha KV, Muthukumar B. Dimensional accuracy of vinyl polyether and polyvinyl siloxane impression materials in direct implant impression technique for multiple dental implants. *Eur Oral Res.* 2021;55(2):54-9.
75. Albayrak B, Sukotjo C, Wee AG, Korkmaz İ H, Bayındır F. Three-Dimensional Accuracy of Conventional Versus Digital Complete Arch Implant Impressions. *J Prosthodont.* 2021;30(2):163-70.
76. Németh A, Vitai V, Czumbel ML, Szabó B, Varga G, Kerémi B, et al. Clear guidance to select the most accurate technologies for 3D printing dental models - A network meta-analysis(☆). *J Dent.* 2023;134:104532.
77. Schwindling FS, Bechtel KN, Zenthöfer A, Handermann R, Rammelsberg P, Rues S. In-vitro fit of experimental full arch restorations made from monolithic zirconia. *J Prosthodont Res.* 2022;66(2):258-64.
78. McLean JW, von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. *Br Dent J.* 1971;131(3):107-11.

79. Lyu J, Yang X, Li Y, Tan J, Liu X. Dimensional accuracy and clinical adaptation of monolithic zirconia crowns fabricated with the nanoparticle jetting technique. *J Prosthet Dent*. 2024;132(5):985.e1-.e7.
80. Katsoulis J, Takeichi T, Sol Gaviria A, Peter L, Katsoulis K. Misfit of implant prostheses and its impact on clinical outcomes. Definition, assessment and a systematic review of the literature. *Eur J Oral Implantol*. 2017;10 Suppl 1:121-38.
81. Abdelrehim A, Etajuri EA, Sulaiman E, Sofian H, Salleh NM. Magnitude of misfit threshold in implant-supported restorations: A systematic review. *J Prosthet Dent*. 2024;132(3):528-35.
82. Borbola D, Berkei G, Simon B, Romanszky L, Sersli G, DeFee M, et al. In vitro comparison of five desktop scanners and an industrial scanner in the evaluation of an intraoral scanner accuracy. *J Dent*. 2023;129:104391.
83. Zhang YJ, Shi JY, Qian SJ, Qiao SC, Lai HC. Accuracy of full arch digital implant impressions taken using intraoral scanners and related variables: A systematic review. *Int J Oral Implantol (Berl)*. 2021;14(2):157-79.
84. Cappare P, Sannino G, Minoli M, Montemezzi P, Ferrini F. Conventional versus Digital Impressions for Full Arch Screw-Retained Maxillary Rehabilitations: A Randomized Clinical Trial. *Int J Environ Res Public Health*. 2019;16(5).
85. Schmalzl J, Róth I, Borbély J, Hermann P, Vecsei B. The impact of software updates on accuracy of intraoral scanners. *BMC Oral Health*. 2023;23(1):219.

16. BIBLIOGRAPHY OF THE CANDIDATE'S PUBLICATIONS

16.1. Publications related to the thesis

1. **Váankos B**, Qian X, Kelemen K, Mikulás K, Kói T, Tóth R, Agócs G, Varga G, Hegyi P, Hermann P, Kispélyi B. Accuracy of conventional versus additive cast-fabrication in implant prosthodontics: A systematic review and meta-analysis of in vitro studies. **Journal of Prosthodontic Research** 2025 Apr 14;69(2):163-172.

http://doi.org/10.2186/jpr.JPR_D_23_00261

D1, IF: 3.4

2. **Váankos, B.** L., Qian, X., Kelemen, K., Szentes, B. L., Agócs, G., Varga, G., Hegyi, P., Hermann, P., & Kispélyi, B. (2026). Accuracy of Digital and Conventional Implant Impressions in Edentulous Jaws: A Systematic Review and Meta-Analysis of In Vitro Studies. **Dentistry Journal**, 14(5), 304.

<https://doi.org/10.3390/dj14050304>

Q1, IF: 3.1

16.2. Publications not related to the thesis

1. **Váankos B**, Palaszko D, Kelemen K, Németh A, Schmalzl J, Zentai DM, Dinya E, Hermann P, Kispélyi B. Enhancing Implant Prosthodontics: In Vitro Accuracy of Coded Healing Abutments on the Edentulous Lower Jaw. **Clinical Implant Dentistry and Related Research** 2025 Jun;27(3):e70036. doi: 10.1111/cid.70036. PMID: 40347045; PMCID: PMC12063562.

D1, IF: 4

2. Qian X, **Váankos B**, Kelemen K, Gede N, Varga G, Hegyi P, Gerber G, Hermann P, Joób-Fancsaly Á, Mikulás K. Comparison of implant placement and loading protocols for single anterior maxillary implants: A systematic review and network meta-analysis. **Journal of Prosthetic Dentistry** 2025 Mar;133(3):677-688. doi:

10.1016/j.prosdent.2024.05.033. Epub 2024 Jul 25. PMID: 39054170.

D1, IF: 4.8

3. Palaszko D, Németh A, Török G, Vecsei B, **Váankos B**, Dinya E, Borbély J, Marada G, Hermann P, Kispélyi B. Trueness of five different 3D printing systems including budget- and professional-grade printers: An In vitro study. **Heliyon**. 2024 Feb 23;10(5):e26874. doi: 10.1016/j.heliyon.2024.e26874. PMID: 38468926; PMCID: PMC10925989.

Q1, IF: 3.6

4. Qian, X., **Váankos, B.**, Agócs, G., Kelemen, K., Wenning, A. S., Kispélyi, B., Gerber, G., Varga, G., Hermann, P., Hegyi, P., Sculean, A., Gallucci, G. O., & Mikulás, K. (2026). Individualized healing significantly improves pink esthetics around immediate single implants: A systematic review and meta-analysis. *Periodontology 2000*, 10.1111/prd.70089. Advance online publication. <https://doi.org/10.1111/prd.70089>

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