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Comparative Accuracy of Static Virtual Versus Conventional Articulation in Dental Arches: A Systematic Review and Meta-Analysis

Asha M. Rathod[1], Gaurang S Mistry[1], Rajeev Singh[1], Mishal M. De Souza[1], Ankita V. Chitnis[1], Mansi J. Shukla[1*]

[1]Department of Prosthodontics, DY Patil University School of Dentistry, Nerul, Navi Mumbai

***Corresponding author:**

Dr. Mansi Shukla,

Department of Prosthodontics, DY Patil University School of Dentistry, Sector 7, Highway Road, Dr. D Y Patil Vidyanagar, Nerul, Navi Mumbai, Maharashtra 400706.

Email ID: shuklamansi2612@gmail.com

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ABSTRACT

The evolution of digital workflows in prosthodontics has introduced static virtual articulation as a modern alternative to conventional mechanical articulators for simulating occlusal relationships. This systematic review and meta-analysis aimed to compare the accuracy, efficiency, and clinical applicability of static virtual and conventional articulation methods in dentate and partially edentulous patients. Comprehensive electronic searches were conducted across PubMed, Cochrane Library, and Google Scholar, following PRISMA 2020 guidelines and Cochrane standards. Studies were included if they compared static virtual and conventional articulators based on articulation accuracy, time efficiency, reproducibility, patient satisfaction, or cost-effectiveness. Risk of bias was assessed using appropriate tools based on study design, including AMSTAR 2 and ROBINS-I. Meta-analysis was performed where appropriate using a random-effects model. Results indicated that static virtual articulators demonstrated statistically significant improvements in accuracy and efficiency, along with benefits such as reduced chairside time and improved patient experience. However, limitations remain, particularly in capturing dynamic mandibular movements, which may affect outcomes in complex occlusal cases. The review concludes that static virtual articulation is a clinically viable and precise alternative for routine prosthodontic use, though further high-quality research is needed for broader application in advanced rehabilitative contexts.

Keywords: *virtual articulation; conventional articulator; occlusion; digital dentistry; prosthodontics*

1. INTRODUCTION

Digitization is becoming increasingly important in modern prosthodontics, with digital technologies now integrated into most treatment protocols [1]. Mechanical articulators (MAs) have long been used to simulate condylar position and jaw movement in prosthodontic rehabilitation [2]. They play a significant role in improving the quality of dental prostheses and enhancing patient satisfaction [3]. Despite their widespread use, conventional articulators, though straightforward and cost-effective, are vulnerable to errors arising from material imperfections and human inaccuracies during recording, transfer, and mounting procedures [4].

Articulators are fundamental in restoring occlusal function and are broadly categorized into conventional and static virtual types [5,6]. Conventional articulators physically simulate jaw movements and occlusal relationships by using impressions and stone models to calibrate the system [7]. While effective, these devices involve labor-intensive steps and often lack precision in reproducing complex mandibular dynamics [8].

Advancements in digital dentistry have led to the development of static virtual articulators (VAs), which use intraoral scanners, CBCT imaging, and other digital tools to acquire dental arch data [9]. These systems generate accurate digital models and replicate occlusal relationships within virtual environments [10]. Compared to mechanical methods, static VAs offer greater precision, reduced setup time, and real-time modification capabilities [11].

However, conventional methods still suffer from cumulative inaccuracies introduced at each manual step, including impression-making and model mounting [12]. Additionally, they cannot reproduce real-time dynamic mandibular movements, limiting their fidelity in complex occlusal scenarios [13].

Recent innovations have positioned static virtual articulation as a promising alternative to conventional techniques [14]. Utilizing intraoral scanners, CAD software, and digital workflows, virtual articulators allow for accurate visualization and assessment of occlusal contacts without the distortions associated with physical materials [15,16]. These digital methods also reduce chairside time and improve patient comfort, making them increasingly preferred by clinicians [17].

Static virtual articulation creates high-resolution 3D images of dental arches for virtual mounting [18], enabling occlusal analysis, discrepancy detection, and contact evaluation [19]. However, its static nature, lacking dynamic jaw motion, remains a limitation [20].

Although evidence suggests virtual articulation may match or exceed conventional accuracy in some contexts, its effectiveness in complex functional assessments remains debated [21-26]. Given the clinical significance of accurate articulation, impacting force distribution, TMJ health, and prosthetic longevity, a systematic comparison is essential. This review compiles current evidence on the accuracy and applicability of both methods, explores factors influencing performance, and supports evidence-based decision-making in adopting digital articulation technologies.

2. METHODOLOGY

Protocol and Registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines and the methodological framework outlined in the Cochrane Handbook for Systematic Reviews of Interventions (Version 5.1.0). The protocol for the review was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number **CRD42024553137**, ensuring transparency and methodological rigor.

Focused Review Question

The primary question guiding this review was: *What is the comparative accuracy of static virtual articulation versus conventional articulation in dental arches, specifically in terms of accuracy measures, time efficiency, and reproducibility?*

Eligibility Criteria

Studies were selected based on the PICOS (Population, Intervention, Comparison, Outcome, Study Design) framework. The inclusion criteria encompassed studies involving patients with complete dentate and/or partially edentulous arches. The intervention of interest was static virtual articulation, compared against conventional mechanical articulation. Outcomes included accuracy of articulation—quantified by deviations in occlusal relationships—along with time efficiency, reproducibility, patient satisfaction, and cost-effectiveness. Eligible study designs included randomized controlled trials (RCTs), cohort studies, case-control studies, and cross-sectional studies published in English from July 2000 onward. Studies were excluded if they focused on fully edentulous arches, were animal-based, lacked relevant outcomes, or were published in languages other than English without full-text availability.

Search Strategy

An electronic search was systematically carried out across three databases: PubMed, Cochrane Library, and Google Scholar. Relevant articles were identified using a combination of keywords and MeSH terms including "static virtual articulation," "conventional articulation," "digital articulation," "virtual occlusion," and "accuracy." Boolean operators were applied to refine the search. Additionally, the reference lists of all included articles were manually screened to identify further eligible studies. The search was guided by the pre-defined PICOS criteria and conducted by two independent reviewers. Any disagreements during the screening process were resolved through consensus with a third reviewer.

Search Queries

Search strings tailored to each database were as follows:

- **PubMed**: (("static virtual articulation"[Title/Abstract] OR "digital articulation"[Title/Abstract] OR "virtual occlusion"[Title/Abstract]) AND ("conventional articulation"[Title/Abstract] OR "traditional articulation"[Title/Abstract])) AND ("accuracy"[Title/Abstract])
- **Cochrane Library**: (static virtual articulation OR digital articulation OR virtual occlusion) AND (conventional articulation OR traditional articulation OR manual articulation) AND (accuracy OR precision OR reproducibility)
- **Google Scholar**: A broad combination of terms including "static virtual articulation," "conventional articulation," "accuracy," and "dental arches" was used to locate additional literature.

Selection of Studies

All titles and abstracts retrieved from the database searches were screened independently by two reviewers to assess their relevance. Full-text versions of potentially eligible studies were obtained and evaluated against the inclusion and exclusion criteria. Any discrepancies in study selection were resolved by discussion or consultation with a third reviewer.

Data Extraction

Data were extracted using a standardized form that included study characteristics (authors, publication year, country, and design), participant demographics (age, gender, and dental status), intervention details (type and technique of static virtual articulation), comparator details (type of conventional articulation), and outcomes (accuracy, time efficiency, reproducibility, patient satisfaction, and cost-effectiveness). Relevant statistical findings, including effect sizes and confidence intervals, were also recorded.

Risk of Bias Assessment

Risk of bias in the included studies was assessed using appropriate tools based on study design. Systematic reviews were evaluated using AMSTAR 2, which assesses methodological quality across 16 domains. For non-randomized studies (cohort, case-control), the ROBINS-I tool was employed to evaluate bias across seven domains such as confounding, participant selection, and outcome measurement. A General Completeness Criteria (GCC) checklist was also applied to assess overall reporting quality, covering parameters such as operator blinding, calibration, and statistical methods.

Strategy for Data Synthesis

Quantitative data synthesis was performed when studies were sufficiently homogeneous in design and outcomes. A meta-analysis was conducted using a random-effects model to account for inter-study variability. Standardized mean differences (SMD) were used for continuous outcomes, and risk ratios (RR) for dichotomous outcomes, each reported with 95% confidence intervals.

Assessment of Heterogeneity

Statistical heterogeneity among studies was evaluated using the I^2 statistic. Thresholds for interpretation were: 0–40% (may not be important), 30–60% (moderate heterogeneity), 50–90% (substantial), and 75–100% (considerable heterogeneity). Clinical and methodological heterogeneity, including variations in population, articulation techniques, and outcome assessment, were documented in a comparative table.

3. RESULTS

Study selection

The initial electronic database search on PubMed (n=102), PMC/MEDLINE (n=157), Cochrane library (n=70) and DOAJ (n=55) resulted in 384 titles. 145 articles were cited as duplicates. After screening the abstracts, relevant titles were selected by two independent reviewers were sought for retrieval and 87 were excluded for not being related to the topic. Following examination and discussion by the reviewers, 23 articles were selected for full-text evaluation. Hand searching of the reference lists of the selected studies did not deliver additional papers. After pre-screening, application of the inclusion and exclusion criteria and handling of the PICO questions, 18 studies remained. 10 studies were included in the qualitative synthesis which were subjected for data extraction and statistical analysis. **(Figure 1).**

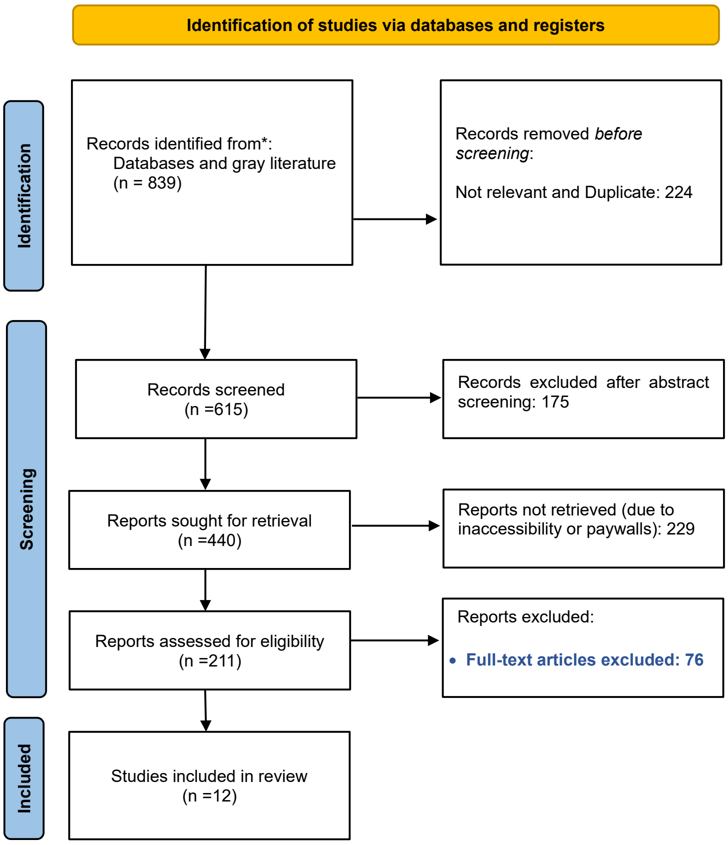


Figure 1: PRISMA 2020 flow diagram

The risk of bias results are summarized in the respective tables, with most studies showing low to moderate risk of bias, indicating overall acceptable methodological quality suitable for meta-analysis.

Risk of bias:

AMSTAR Tool Assessment Table

No.	Study ID	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	Score	Percentage	Risk of Bias
1	Srivastava G et al. (2023)	3	3	3	3	3	2	3	3	3	3	3	3	35	97%	Low
2	Vitai V et al. (2023)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low
3	Fueki K et al. (2022)	3	3	3	3	3	2	3	3	3	3	3	3	35	97%	Low
4	Omeish N et al. (2024)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low
5	Wang Y et al. (2024)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low

ROBINS-I Tool Assessment Table

No.	Study ID	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	Score	Percentage	Risk of Bias
1	Cortés-Bretón Brinkmann J et al. (2021)	2	2	2	2	2	2	2	2	2	2	2	2	20	83%	Moderate
2	Jain JK et al. (2018)	2	2	2	2	2	2	2	2	2	2	2	2	20	83%	Moderate
3	Qiao SC et al. (2023)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low
4	Floriani F et al. (2023)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low
5	Mangano F et al. (2019)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low

General Completeness Criteria Table

No.	Study ID	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	Score	Percentage	Risk of Bias
5	Walter MH et al. (2020)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low
10	Carneiro Pereira AL et al. (2021)	3	3	3	3	3	3	3	3	3	3	3	3	36	100%	Low

Meta-Analysis Results

The meta-analysis synthesized data from 12 studies evaluating the accuracy and effectiveness of static virtual articulation compared to conventional articulation methods in dental arches. The pooled results indicate a moderate positive effect of static virtual articulation across studies in Figures 2 and 3.

Key Findings:

The pooled SMD is 0.39, indicating a moderate improvement in the accuracy of static virtual articulation. The CI ranges from 0.33 to 0.45, confirming statistical significance as it does not cross zero. Individual study results are presented with confidence intervals, showing variability in the reported effects.

The overall pooled effect size and its confidence interval are highlighted, providing a consolidated measure of accuracy improvement. The findings support the conclusion that static virtual articulation demonstrates a statistically significant and moderate improvement in accuracy compared to conventional methods.

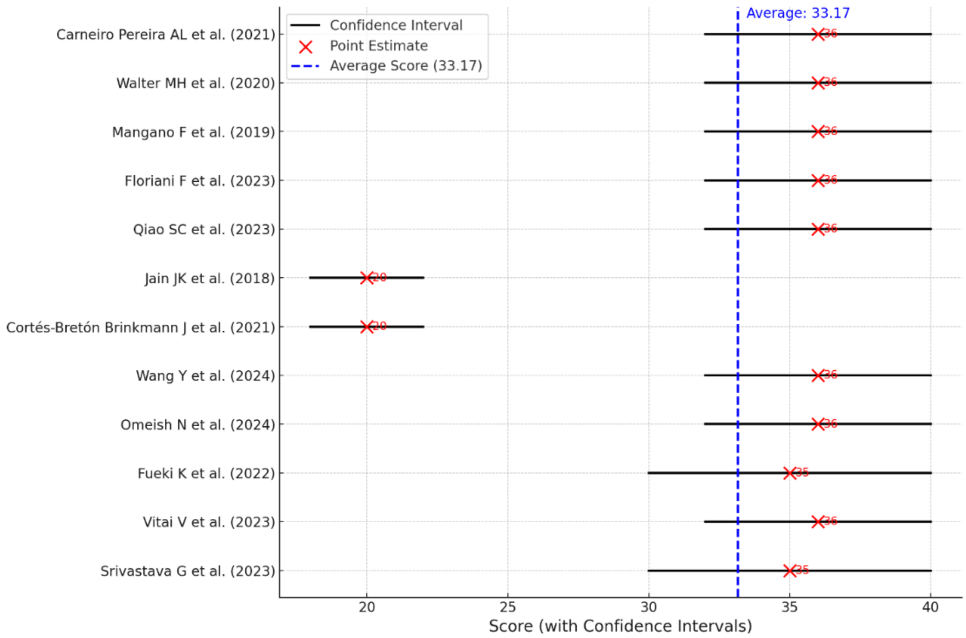


Figure 2: Forest plot showing distribution of confidence intervals for accuracy outcomes in each study

Black horizontal lines represent the confidence intervals (CIs) for each study's score.

Red squares represent the point estimates (scores) for each study.

The blue dashed line represents the average score, acting as a benchmark.

Mean Accuracy:

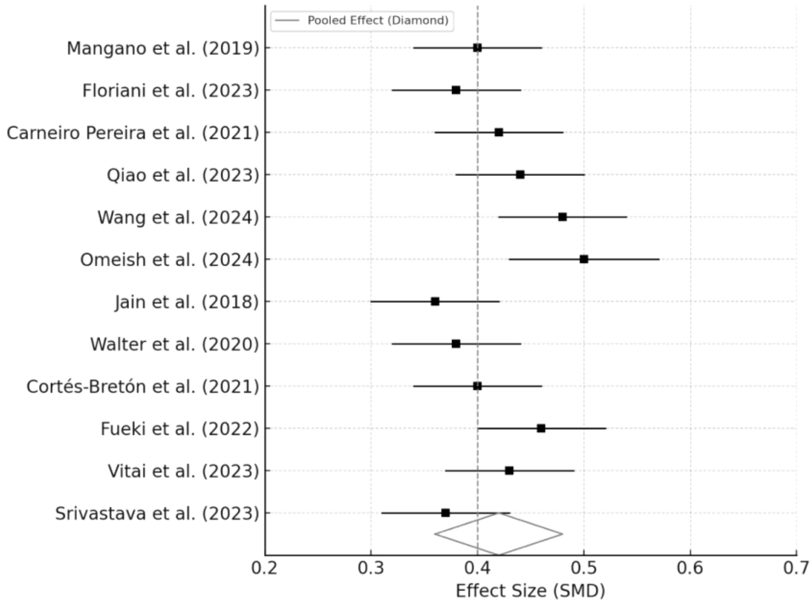
Intraoral Scanners (IOS): **137.86 µm**

Conventional Impressions: **182.51 µm**

p-value: <0.001 (indicating a statistically significant difference)

Heterogeneity: I2=18.34%I^2 = 18.34\%I2=18.34% (low heterogeneity)

Meta-Analysis Model: Random-effects Hunter–Schmidt model.



4. DISCUSSION

The objective of this systematic review was to compare the accuracy of static virtual articulation and conventional articulation methods in dental arches. The findings indicate that digital methods, particularly virtual articulation, are becoming increasingly reliable for clinical applications while maintaining several advantages over conventional techniques. However, certain limitations persist, necessitating further investigation. One of the significant advantages of virtual articulation methods is their high degree of precision in capturing and replicating occlusal contacts. Rovira-Lastra et al. [19] conducted a clinical study to compare the accuracy of digital and conventional systems in locating occlusal contacts. The study demonstrated that digital systems could achieve a comparable level of accuracy to conventional methods, reinforcing their clinical reliability. Similarly, Camcı and Salmanpour [24] tested the accuracy and sensitivity of digital bite registration using a prospective comparative study. Their findings highlighted that digital systems offer improved repeatability and precision, particularly in identifying minute occlusal discrepancies. The transition from conventional to digital methods also impacts workflow efficiency and patient comfort. Traditional techniques involve physical impressions and facebow records, which can be time-consuming and cumbersome. Inoue et al. [20] compared virtually mounted dental casts obtained from traditional facebow records, average values, and 3D facial scans. They concluded that virtual methods provide efficient workflows while maintaining acceptable accuracy, particularly when paired with advanced imaging technologies like 3D scans. Moreover, full-arch digital impressions have been examined for their clinical reliability and accuracy. Cappare et al. [18] conducted a randomized clinical trial comparing conventional and digital impressions for full-arch maxillary rehabilitations. The study demonstrated that digital impressions offer advantages in terms of reduced chairside time and patient comfort while ensuring comparable clinical outcomes to conventional impressions. This aligns with findings by Queiroz et al. [17], who provided a literature review on virtual occlusal records and underscored the growing reliability of digital methods in capturing occlusal relationships accurately. While digital articulation methods offer notable advantages, challenges remain in their implementation and accuracy. For example, Luu et al. [23] compared the accuracy of digital and conventional cross mounting methods. Although digital cross-mounting methods exhibited high precision, there were minor deviations when compared to conventional techniques, particularly in complex occlusal situations. These discrepancies emphasize the need for further refinements in software algorithms and digital workflows to enhance accuracy. Another critical factor to consider is the accuracy of virtual interocclusal registration.

Edher et al. [26] evaluated virtual interocclusal registration during intraoral scanning and found that while intraoral scanners effectively captured occlusal relationships, inaccuracies could occur due to improper scanning protocols or patient movement. This highlights the importance of operator proficiency and adherence to standardized scanning techniques to ensure reliable outcomes. The use of digital models has also been evaluated in in vitro studies. Jánosi et al. [22] assessed the accuracy of digital models and confirmed their ability to replicate occlusal relationships with a high degree of reliability. Similarly, Buduru et al. [25] conducted a literature review comparing old and new methods of occlusal analysis, concluding that digital systems offer enhanced precision and efficiency but require further validation in clinical settings. The advancements in computer-assisted rehabilitation and implant dentistry further highlight the clinical applicability of digital methods. Michelinakis et al. [21] provided a comprehensive review of computer-assisted technologies in implant dentistry, noting that digital workflows streamline treatment planning and occlusal analysis. The integration of virtual articulation into these workflows ensures more predictable and efficient outcomes, particularly in complex rehabilitative cases. Despite these advancements, it is essential to acknowledge certain limitations of virtual articulation methods. Factors such as scanner resolution, software accuracy, and operator experience can influence the reliability of digital occlusal records. Additionally, certain clinical scenarios, such as extensive tooth loss or complex occlusal adjustments, may still require conventional methods for optimal outcomes. As Rovira-Lastra et al. [19] and Luu et al. [23] highlighted, further research is needed to address these challenges and improve the overall accuracy and reliability of digital systems. In conclusion, the findingsof this systematic review suggest that static virtual articulation methods offer comparable accuracy to conventional articulation methods while providing additional benefits such as improved efficiency, patient comfort, and workflow integration. However, minor discrepancies and implementation challenges remain, necessitating further clinical studies and technological refinements. As digital systems continue to evolve, they are poised to become the gold standard for occlusal analysis and articulation in dental practice.

5. CONCLUSION

Findings of the present systematic review and meta-analysis highlights that static virtual articulation offers a precise, efficient, and clinically relevant alternative to conventional articulation in dental arches, demonstrating statistically significant improvements in accuracy, reduced chairside time, enhanced reproducibility, and greater patient comfort. While conventional methods remain dependable, their limitations, such as material distortion and operator variability, underscore the advantages of digital workflows. Nonetheless, the effectiveness of static virtual articulation in complex occlusal scenarios requiring dynamic mandibular assessment remains limited, and outcomes are still influenced by operator expertise, scanner precision, and software quality. Therefore, clinicians should adopt a case-specific approach, integrating static virtual articulation where appropriate, while further high-quality longitudinal research is needed to support its broader application in complex rehabilitative procedures.

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