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Trueness and Precision of Milled versus 3D-Printed Hybrid Crowns: A Narrative Review of Digital Manufacturing Accuracy

Mohamed Hussein Mohamed Hussein, Soha Osama Nabih, Amr El-Etreby

Fixed Prosthodontics Department, Faculty of Dentistry, Ain Shams University, Cairo, Egypt.

Abstract

The integration of digital technologies into fixed prosthodontics has facilitated the widespread adoption of computer-aided design and computer-aided manufacturing (CAD/CAM) systems for crown fabrication. Among emerging approaches, additive manufacturing has gained increasing attention as a potential alternative to conventional subtractive milling, particularly when combined with hybrid restorative materials. Nevertheless, the comparative accuracy of these manufacturing techniques remains inconclusive. This narrative review evaluates the current evidence on the trueness and precision of crowns fabricated from hybrid materials using both milling and three-dimensional printing. A literature search was conducted using PubMed, Scopus, and Web of Science, focusing on studies related to CAD/CAM workflows, additive manufacturing (3D printing), subtractive techniques (milling), hybrid materials, and accuracy assessment parameters, including trueness and precision. Current evidence reports that digital workflows have enhanced the predictability and reproducibility of fixed prosthodontic restorations, with both techniques producing crowns within clinically acceptable accuracy ranges. Most studies report higher trueness in milled restorations, while additive manufacturing demonstrates greater precision and reproducibility; however, these findings are not consistent across all investigations and do not necessarily translate into superior clinical performance. The relationship between manufacturing technique and accuracy remains complex, particularly in hybrid materials, whose unique structure may influence fabrication outcomes. Interpretation of existing findings is further limited by methodological variability and the lack of standardized evaluation protocols. Within these limitations, both manufacturing techniques can be considered clinically reliable for hybrid crown fabrication. Therefore, the choice of technique should be guided by a comprehensive assessment of accuracy, material characteristics, and workflow considerations rather than reliance on a single parameter. Future research should emphasize standardized methodologies and well-designed clinical studies to better clarify the clinical relevance of observed differences.

Keywords: CAD/CAM; 3D printing; milling; hybrid materials; trueness; precision; dental crowns

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1. Introduction

The increasing integration of digital technologies into fixed prosthodontics has reshaped contemporary restorative practice, allowing a gradual shift from conventional analog workflows to more standardized and efficient digital approaches. Computer-aided design and computer-aided manufacturing (CAD/CAM) systems now play a central role in crown fabrication, improving communication between clinicians and laboratories while enhancing consistency in production. Despite these advances, the clinical success of digitally fabricated restorations still depends largely on their dimensional accuracy, as even minor discrepancies may compromise marginal integrity, cement performance, and long-term biological outcomes [1-3].

1.1. CAD/CAM in Fixed Prosthodontics

Digital workflows in fixed prosthodontics typically involve three interrelated stages: data acquisition, virtual design, and manufacturing. In recent years, intraoral scanning has increasingly replaced conventional impression techniques, reducing errors associated with material distortion and cast fabrication. The acquired digital data are then processed using CAD software, where critical parameters—such as margin delineation, cement space, and occlusal morphology—are defined. It is important to recognize that inaccuracies introduced at any of these stages may propagate throughout the workflow and ultimately affect the fit of the final restoration [4-7] .The digital workflow of CAD/CAM crown fabrication is illustrated in Figure 1.

1.2. Manufacturing Techniques

The transformation of digital designs into physical restorations can be achieved through either subtractive or additive manufacturing approaches. Subtractive manufacturing, commonly referred to as milling, involves removing material from prefabricated blocks using computer-controlled tools. This method is generally associated with predictable material behavior and high dimensional stability

[8-9]. By contrast, additive manufacturing builds restorations layer by layer using technologies such as stereolithography and digital light processing. This approach offers greater design flexibility and reduced material waste; however, it also introduces additional variables—including layer thickness, build orientation, and polymerization behavior—that may influence final accuracy [10-12]. The fundamental differences between subtractive and additive manufacturing are shown in Figure 2.

1.3. Hybrid Materials

Parallel to these technological developments, hybrid restorative materials have emerged as an alternative to conventional ceramics and composites. These materials integrate ceramic and polymer components within a single structure, aiming to combine strength with resilience and improved machinability. Their elastic behavior, which more closely resembles dentin, may offer advantages in stress distribution. However, their response to different manufacturing techniques is not yet fully understood [13-15]. Examples of commercially available hybrid restorative materials used in subtractive and additive manufacturing are summarized in Table 2.

1.4. Trueness and Precision

Accuracy in digital prosthodontics is commonly described using two complementary concepts: trueness and precision. Trueness reflects how closely a fabricated restoration matches its original digital design, whereas precision refers to the consistency observed among repeated restorations produced under identical conditions. Although closely related, these parameters describe different aspects of accuracy and should not be interpreted interchangeably [16-18]. The conceptual difference between trueness and precision is illustrated in Figure 3.

1.5. Measurement of Accuracy

A variety of methods have been used to assess accuracy in digitally fabricated restorations. Three-dimensional comparison techniques are widely employed to quantify deviations between datasets, often expressed as root mean square (RMS) values. In addition, physical methods such as replica techniques and micro-computed tomography can provide detailed insights into marginal and internal fit. However, differences in evaluation protocols across studies limit direct comparison of results and contribute to variability in reported outcomes [17-20].

1.6. Aim of the Review

This narrative review explores the current evidence on the trueness and precision of crowns fabricated from hybrid materials using both subtractive (milling) and additive (three-dimensional printing) techniques. Rather than simply summarizing findings, it seeks to bring together the available data to highlight patterns of agreement, identify inconsistencies among studies, and consider how these differences may influence clinical outcomes [21-24]. To support this analysis, a literature search was carried out using electronic databases, including PubMed, Scopus, and Web of Science. The search focused on studies related to digital workflows, manufacturing approaches, hybrid restorative materials, and methods used to assess accuracy.

2. Literature Review

A substantial number of studies have explored the accuracy of digitally fabricated crowns, particularly in relation to the performance of subtractive and additive manufacturing techniques when applied to hybrid restorative materials.

2.1. Trueness of Milled and 3D-Printed Hybrid Crowns

Trueness is a key indicator of manufacturing accuracy, reflecting how closely a fabricated restoration corresponds to its original digital design. A substantial body of research has examined this parameter in both subtractive and additive manufacturing, with most studies reporting higher trueness in milled restorations. Son and Lee et al. [19] compared the marginal and internal fit of crowns produced by milling and three-dimensional printing using three-dimensional superimposition analysis. Their findings indicated that milled crowns exhibited lower deviation values, indicating closer agreement with the reference design. This observation has often been attributed to the dimensional stability of prefabricated CAD/CAM blocks and the controlled nature of the milling process.More recent investigations have reported similar results. Lerner et al. [24] evaluated the trueness and precision of milled and three-dimensionally printed monolithic zirconia crowns and found that milled restorations exhibited higher trueness. However, both manufacturing techniques produced restorations within clinically acceptable limits, and no substantial differences in precision were observed. These findings further support the view that, although findings across studies are inconsistent, their clinical relevance remains limited under controlled conditions. Systematic reviews further support the interpretation that differences between techniques are inconsistent across studies.

Papadiochou and Pissiotis [22] reported that CAD/CAM restorations generally achieve acceptable marginal adaptation regardless of fabrication method, with variations largely dependent on study design and evaluation protocols. Similarly, Joda et al. [21] emphasized that restoration accuracy is influenced not only by the manufacturing technique but also by the overall digital workflow, including scanning and clinical handling. From a materials perspective, Revilla-León and Özcan et al. [10] highlighted polymerization shrinkage and light-curing variability as potential sources of dimensional distortion in additively manufactured restorations. Tahayeri et al. [12] further reported that post-curing protocols may influence dimensional stability and, consequently, trueness. It is important to note, however, that not all studies report consistent differences between manufacturing techniques. Some investigations report that trueness is comparable in some studies under controlled conditions, reflecting the influence of methodological variability across studies. Overall, while milling shows higher trueness in most studies, the magnitude and clinical relevance of these differences are inconsistent across studies.Despite these limitations, several studies have pointed out that deviations associated with additive manufacturing often remain within clinically acceptable limits.

For example, Son and Lee et al. [19] reported that although 3D-printed crowns exhibited greater deviation, these differences did not exceed thresholds considered acceptable for clinical use. Milling, on the other hand, is generally considered to benefit from a more controlled fabrication environment. Bindl and Mörmann et al. [8] demonstrated that CAD/CAM-milled restorations achieve high marginal and internal accuracy, largely due to the uniformity of industrially produced materials and the absence of polymerization-related distortions. However, this technique is not without limitations, as factors such as bur diameter, tool wear, and machine calibration may still introduce minor discrepancies, particularly in regions with intricate geometry. Taken together, most studies report that the higher trueness often observed in milling is related to its subtractive nature, which reduces several sources of variability inherent in additive manufacturing. At the same time, the accuracy of 3D printing is highly dependent on process parameters such as layer thickness, build orientation, and post-processing conditions. Some investigations have reported minimal or no statistically significant differences between the two techniques under controlled conditions [21-22], highlighting the influence of methodological variability across studies. Overall, while milling is often regarded as a reference approach for achieving high trueness, magnitude of these differences is frequently comparable and may not always translate into clinically meaningful advantages.

2.2. Precision and Reproducibility of Milled and 3D-Printed Hybrid Crowns

Precision, often described as reproducibility, refers to the ability of a manufacturing technique to consistently produce restorations with minimal variation under identical conditions. Unlike trueness, which reflects agreement with a reference design, precision captures the consistency of repeated outputs and is therefore essential when evaluating the reliability of digital workflows. In both CAD/CAM and additive manufacturing systems, this parameter is influenced by factors such as machine stability, material characteristics, and process standardization. Several studies report that additive manufacturing exhibits high levels of precision under controlled conditions, with some investigations reporting higher reproducibility compared with subtractive techniques. Son and Lee et al. [19], for example, reported lower variability among 3D-printed crowns compared with milled counterparts, indicating more consistent reproduction. This has often been attributed to the automated and standardized nature of the printing process, which minimizes operator-dependent factors and eliminates variability associated with mechanical tool wear. However, findings from Lerner et al. [24] indicate that differences in precision between the two techniques are often not significant. In their study, no substantial differences in precision were observed between milled and three-dimensionally printed restorations, despite variations in trueness. This indicates that, although manufacturing techniques may differ in their agreement with reference design, both approaches can achieve comparable levels of reproducibility under controlled conditions.

These observations are also supported indirectly by broader analyses of digital workflows, which report that process standardization in additive manufacturing contributes to more consistent outcomes [21-22]. In this context, several studies have reported that once printing parameters are properly standardized, additively manufactured crowns exhibit reproducible results across multiple specimens. The layer-by-layer fabrication process supports this reproducibility, provided that processing conditions remain stable. By comparison, milling involves direct physical interaction between cutting tools and the material, which introduces additional sources of variability, particularly over time as tool wear and machine-related factors come into play. Further support comes from Alharbi et al. [11-20], who demonstrated that 3D printing systems can produce restorations with consistent marginal and internal discrepancies across repeated builds. Their findings emphasize that, unlike milling, additive manufacturing does not rely on tools that degrade over time, allowing reproducibility to be maintained even during extended production cycles. In contrast, the precision of milling is affected by mechanical and operational factors. Abduo et al. [9] highlighted influence of bur wear, machine calibration, and thermal effects, all of which can reduce consistency over time. As cutting instruments undergo repeated use, their ability to reproduce fine details may gradually decline, leading to increased variability between restorations.

The geometry of milling tools also imposes inherent limitations. The finite diameter of burs restricts the accurate reproduction of sharp internal features, which may necessitate compensatory adjustments during fabrication. These adjustments can introduce small variations, particularly in restorations with complex geometries. Despite these constraints, milling continues to demonstrate clinically acceptable levels of precision. Bindl and Mörmann et al. [8] noted that, although some variability exists, milled restorations generally maintain consistent dimensional accuracy within acceptable clinical thresholds. This indicates that while milling may be less reproducible than additive manufacturing, it remains sufficiently reliable for routine clinical use. An important advantage of additive manufacturing lies in its non-contact fabrication process. Because restorations are built without mechanical interaction, tool-related variability is eliminated. However, reproducibility in 3D printing is still dependent on stable processing conditions. Variations in light intensity, resin composition, or environmental factors affect outcomes if not adequately controlled. Overall, precision in the two manufacturing techniques arises from different underlying mechanisms. Milling variability is largely mechanical, whereas additive manufacturing variability is process-driven. As a result, 3D printing was reported to show higher reproducibility under controlled conditions, while milling exhibits gradual variability over time. Nevertheless, both approaches produce restorations with acceptable consistency for clinical application.

2.3. Effect of Hybrid Material Properties on Accuracy

The accuracy of digitally fabricated restorations is influenced not only by the manufacturing technique but also by the intrinsic properties of the materials used. Hybrid materials, which combine ceramic and polymer phases within a single structure, present distinct mechanical and physical characteristics that can affect both trueness and precision.

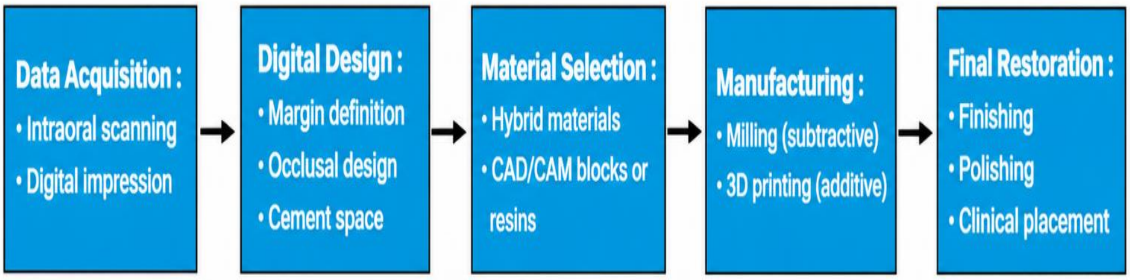

Figure 1. Digital workflow for fabrication of hybrid crowns using CAD/CAM technology, including data acquisition, design, material selection, manufacturing, and final restoration.

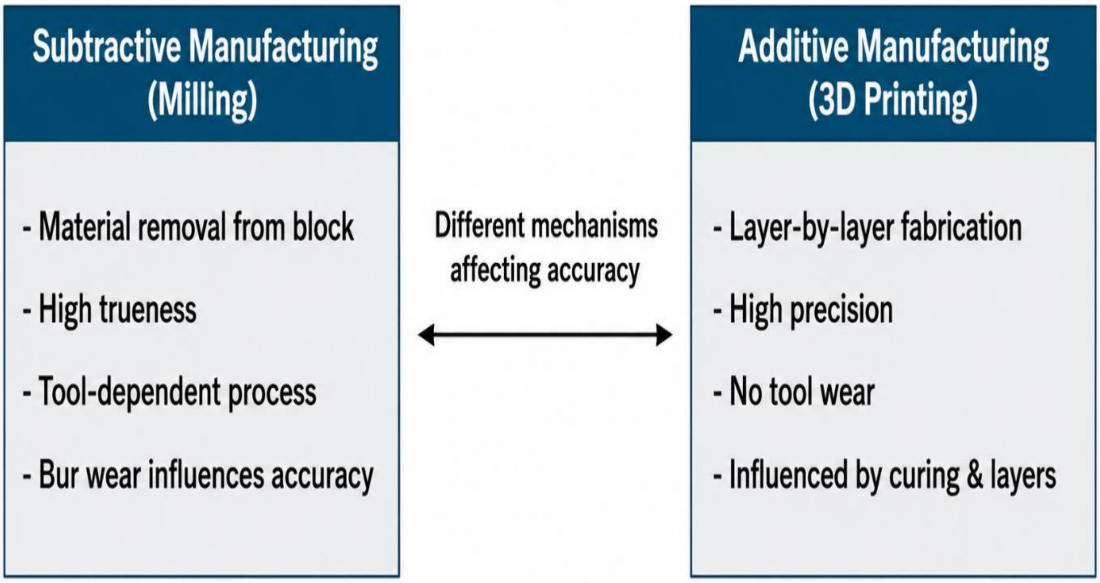

Figure 2. Comparison between subtractive (milling) and additive (3D printing) manufacturing techniques used for hybrid crown fabrication.

Figure 3. Schematic representation of trueness and precision. Trueness describes the deviation from the reference design, while precision reflects the consistency of repeated measurements.

Table 1. Summary of Included Studies on the Accuracy of Milled and 3D-Printed Hybrid Crowns

Study	Parameter	Material	Technique	Key Finding
Son & Lee et al. [19]	Both	Hybrid / Resin-based	Milling vs 3D Printing	Milled crowns demonstrated higher trueness with lower deviation from the CAD design, while 3D-printed crowns showed higher precision, indicating better reproducibility across repeated fabrications.
Lerner et al. [24]	Both	Zirconia	Milling vs 3D Printing	Milled crowns showed higher trueness, whereas both techniques demonstrated comparable precision and clinically acceptable outcomes.
Bindl & Mörmann et al. [8]	Trueness	Ceramic (reference)	Milling	Milling provided high marginal and internal accuracy due to the stability of prefabricated blocks, although minor variability in precision was observed, likely related to machining factors.
Papadiochou et al. [22]	Trueness	CAD/CAM restorations	Both	No clinically meaningful differences were found between milling and 3D printing, as both techniques achieved comparable trueness and precision in marginal fit.
Guess et al. [23]	Trueness	CAD/CAM materials	Milling	Trueness values reported for milled restorations were within clinically acceptable ranges and appeared to be influenced by material homogeneity, while precision was affected by material-related factors impacting dimensional stability.
Revilla-León & Özcan et al. [10]	Precision	Polymer-based	3D Printing	Trueness in additively manufactured restorations may be influenced by polymerization shrinkage and light-curing variability, while precision can remain high when processing parameters are properly controlled.
Tahayeri et al. [12]	Precision	Resin-based	3D Printing	Trueness in 3D-printed restorations was influenced by polymerization behavior, particularly in cases of incomplete or uneven curing, while precision remained high and dependent on post-curing protocols.
Alharbi et al. [11,20]	Precision	Hybrid materials	3D Printing	3D printing demonstrated high reproducibility with acceptable internal adaptation, although moderate deviations in trueness were observed depending on printing settings.
Abduo et al. [9]	Precision	CAD/CAM materials	Milling	Milling initially produced high trueness and precision; however, precision decreased over time due to bur wear, affecting reproducibility.
Joda et al. [21]	Both	Digital workflow	Both	Both techniques were reported to achieve comparable trueness and precision, with internal fit influenced not only by manufacturing accuracy but also by seating dynamics and clinical handling.

CAD/CAM = computer-aided design and computer-aided manufacturing; PICN = polymer-infiltrated ceramic network; SLA = stereolithography; DLP = digital light processing; RMS = root mean square.

Table 2. Commercial Hybrid Restorative Materials Used in Subtractive and Additive Manufacturing

Material / Brand	Manufacturer	Technique	Material type	Manufacturer-Reported properties
Subtractive manufacturing — milling				
VITA ENAMIC [25]	VITA Zahnfabrik	Milling	Polymer-infiltrated ceramic network (PICN)	Enamel-like elasticity, high load-bearing capacity, improved machinability, shock absorption, dentin-like behavior
BRILLIANT Crios [26]	Coltene	Milling	Reinforced composite resin	High flexural strength, excellent polishability, shock absorption, low abrasiveness to opposing dentition, enamel-like elasticity
Lava Ultimate [27]	3M ESPE	Milling	Resin nanoceramic	High fracture resistance, wear resistance, excellent polish retention, resilience, efficient milling performance
Cerasmart [28]	GC Corporation	Milling	Resin-based hybrid ceramic	Flexural behavior, high polishability, wear resistance, marginal adaptation, reduced brittleness
Enamic IS [29]	VITA Zahnfabrik	Milling	Hybrid ceramic	Dimensional stability, elastic behavior, improved stress distribution, efficient machinability
Additive manufacturing — 3D printing				
Permanent Crown Resin [30]	Formlabs	3D Printing	Ceramic-filled photopolymer resin	Designed for permanent restorations, printable accuracy, esthetics, stain resistance, post-curing dependent properties
Crowntec [31]	Saremco	3D Printing	Hybrid composite resin	Biocompatibility, printable reproducibility, esthetics, fracture resistance, low shrinkage behavior
VarseoSmile Crown plus [32]	BEGO	3D Printing	Ceramic-filled hybrid resin	High flexural strength, printable precision, esthetics, biocompatibility, permanent restoration application
Tera Harz TC-80DP [33]	Graphy	3D Printing	Ceramic-reinforced resin	High dimensional stability, printable reproducibility, flexural strength, wear resistance, translucency

Table 3. Factors Influencing Trueness and Precision of Hybrid Crowns Fabricated by Milling and 3D Printing

Factor	Effect in milling (subtractive)	Effect in 3D printing (additive)	Influence on trueness and precision	Supporting studies
Scanner accuracy	Inaccurate scans may produce incorrect margin delineation and internal geometry before milling	Scanning inaccuracies may propagate throughout the printing workflow and affect layer adaptation	Directly affects trueness by increasing deviation from the reference design and may reduce reproducibility	[4-7]
Material composition	Material hardness and brittleness influence machinability, bur interaction, and dimensional stability during milling	Resin composition and ceramic filler content affect polymerization behavior and post-curing stability	Influences both trueness and precision through dimensional stability and consistency of fabrication	[13-15]
Polymerization shrinkage	Not a major factor — prefabricated CAD/CAM blocks are industrially polymerized	Significant factor due to layer curing and post-polymerization contraction	Primarily reduces trueness by increasing dimensional distortion; precision may remain acceptable under standardized curing protocols	[10-12]
Milling bur wear	Progressive bur wear reduces cutting efficiency and accuracy of fine internal details	Not applicable — no cutting tools are used	Mainly decreases precision over time and may slightly affect trueness	[9]
Layer thickness (3D printing)	Not applicable in milling workflows	Increased layer thickness may reduce surface accuracy and increase stair-step effect	Affects both trueness and precision depending on printing resolution and consistency	[11-20]
Build orientation	Not applicable in conventional milling	Incorrect build angulation may introduce distortion, uneven polymerization, and support-related inaccuracies	Influences trueness and reproducibility of printed restorations	[10-12]
Machine calibration	Calibration errors may produce inaccurate tool movement and restoration dimensions	Printer calibration inaccuracies may affect layer positioning and curing consistency	Can negatively affect both trueness and precision in either workflow	[9-12]
Post-processing procedures	Finishing and polishing may introduce minor dimensional alterations after milling	Post-curing conditions strongly affect dimensional stability and polymerization completion	Primarily influences final trueness and long-term reproducibility	[10-12]

Note. *3D = three-dimensional. Numbers in brackets refer to cited references*

Coldea et al. [13] described polymer-infiltrated ceramic-network materials as having a dual-phase structure consisting of a ceramic scaffold reinforced by a polymer At the same time, this structure influences how the material responds during fabrication, particularly with regard to dimensional stability. Mainjot et al. [14] further emphasized that hybrid CAD/CAM materials differ fundamentally from both ceramics and composite resins. The presence of a polymer phase introduces viscoelastic behavior, which can affect both machining performance during milling and dimensional changes during additive manufacturing. As a result, findings from conventional ceramic systems cannot always be directly applied to hybrid materials. From a milling perspective, hybrid materials offer improved machinability. Awada and Nathanson et al. [15] noted that their reduced brittleness lowers the risk of chipping, allowing for more controlled shaping and contributing to the high trueness often observed in milled restorations. In additive manufacturing, however, material behavior becomes more complex. Revilla-León and Özcan et al. [10] highlighted the impact of polymerization shrinkage, which can introduce dimensional changes during fabrication.

In hybrid materials, the polymer component amplifies these effects, particularly during post-curing, potentially reducing trueness. Tahayeri et al. [12] also demonstrated that material composition plays a critical role in determining accuracy. Variations in resin formulation and curing protocols can significantly influence dimensional stability. Materials with higher polymer content exhibit greater shrinkage, whereas optimized formulations can improve overall accuracy. Another important consideration is the elastic modulus of hybrid materials, which more closely resembles that of dentin. This property may allow restorations to better accommodate internal discrepancies during seating, potentially compensating for minor inaccuracies. The interaction between material properties and manufacturing technique is therefore complex. In milling, hybrid materials benefit from their machinability and resistance to fracture. In contrast, in additive manufacturing, their polymer component becomes a dominant factor influencing the dimensional stability.

3. Conclusion

Current evidence indicates that digital workflows have improved the predictability and consistency of fixed prosthodontic restorations, with both milling and three-dimensional printing capable of producing crowns within clinically acceptable accuracy ranges. While most studies report higher trueness in milled restorations, additive manufacturing demonstrates greater precision and reproducibility. However, these differences are not consistent across all investigations and do not always translate into superior clinical outcomes. The relationship between manufacturing technique and accuracy remains complex, particularly when hybrid materials are considered. Their unique polymer–ceramic composition may influence both fabrication behavior and clinical performance, limiting direct comparison with conventional materials. Moreover, the available evidence is constrained by methodological variability and a lack of standardized evaluation protocols, which contribute to inconsistencies across studies. Within these limitations, both approaches can be considered matrix. This configuration provides a balance between strength and flexibility, allowing the material to absorb stress more effectively than traditional ceramics.
clinically reliable. Therefore, the choice of manufacturing technique should be based on a balanced assessment of accuracy, material properties, and workflow efficiency rather than a single performance parameter.

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