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Three-dimensional Printing Versus Milling in Prosthodontics: A Review

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ABSTRACT

Three-dimensional (3D) printing and computer-aided design and computer-aided manufacturing (CAD/CAM) milling have transformed modern prosthodontics by improving the efficiency and precision of dental prosthesis fabrication. This review compares both technologies in terms of material properties, mechanical strength, dimensional accuracy, marginal fit, surface characteristics, and clinical performance. While 3D printing offers design flexibility, reduced material wastage, and efficient fabrication of complex structures, milling provides established workflows and consistent material properties. Their performance varies according to the material, manufacturing parameters, and type of prosthesis. Further comparative studies and long-term clinical evaluations are needed to determine their relative advantages and establish evidence-based recommendations for prosthodontic applications

INTRODUCTION

The integration of digital technologies into prosthodontics has significantly transformed the fabrication of dental restorations, improving workflow efficiency, precision, and treatment planning.[1] Among these technologies, three-dimensional (3D) printing and computer-aided design and computer-aided manufacturing (CAD/CAM) milling have gained considerable attention as alternative approaches to conventional manufacturing techniques. Three-dimensional printing employs an additive manufacturing process in which materials are deposited or polymerized layer by layer, whereas milling uses a subtractive process to shape restorations from prefabricated blocks or discs. Both techniques are used for fabricating crowns, fixed dental prostheses, removable dentures, and implant-supported restorations.[2,3] However, differences in manufacturing principles, material characteristics, dimensional accuracy, mechanical properties, surface quality, fabrication time, and cost may influence their clinical performance. Therefore, this review aims to compare 3D printing and milling in prosthodontics, emphasizing their material properties, manufacturing accuracy, and clinical outcomes to support evidence-based selection of appropriate fabrication techniques.

FUNDAMENTALS OF MANUFACTURING TECHNOLOGIES

Three-dimensional (3D) printing is an additive manufacturing technique that fabricates dental prostheses by building structures layer by layer from a digitally designed model. The process generally begins with intraoral scanning or digitization of a conventional impression, followed by computer-aided design (CAD) of the intended restoration. The digital model is subsequently converted into a standard tessellation language (STL) file, sliced into thin layers using specialized software, and transferred to the printer. After fabrication, the printed component undergoes post-processing, which may include support removal, washing, post-curing, sintering, finishing, and polishing, depending on the material and printing technology used. Several 3D printing techniques are employed in dentistry, including stereolithography (SLA), which uses a laser to selectively polymerize liquid photosensitive resin; digital light processing (DLP), which employs projected light to cure entire layers; and liquid crystal display (LCD) printing, which uses an LCD mask and a light source to polymerize successive layers. Selective laser sintering (SLS) uses a laser to fuse powdered materials, whereas selective laser melting (SLM) produces metal components by melting metallic powder. Fused deposition modeling (FDM) constructs objects by extruding thermoplastic filaments through a heated nozzle. The suitability of each technique depends on the material, dimensional accuracy, mechanical requirements, surface finish, and intended prosthodontic application. These technologies offer advantages such as design flexibility, efficient material utilization, and the fabrication of complex geometries; however, their performance can be influenced by printing parameters, material characteristics, and post-processing protocols.[4,5]

CAD/CAM MILLING

Computer-aided design and computer-aided manufacturing (CAD/CAM) milling is a subtractive manufacturing technique in which a dental restoration is produced by removing material from a prefabricated block or disc using computer-controlled rotary cutting instruments. The process involves digital acquisition of the dental anatomy, virtual restoration design, and transfer of the CAD data to a milling machine for fabrication. Milling systems are classified as wet or dry according to their operating conditions. Dry milling is commonly used for materials such as zirconia and polymethyl methacrylate (PMMA), whereas wet milling employs coolant to reduce heat generation and is frequently used for glass ceramics and certain composite materials, depending on the manufacturer's recommendations. Milling machines may operate using four-axis or five-axis configurations. Four-axis systems provide movement along three linear axes with rotation around one additional axis, while five-axis systems incorporate two rotational axes, allowing improved access to complex geometries and undercuts. Dental restorations are milled from prefabricated blocks or discs composed of materials such as zirconia, lithium disilicate, feldspathic ceramics, PMMA, and resin-matrix composites. This technique offers consistent material quality, reproducible fabrication, and an established workflow for producing crowns, bridges, veneers, and implant-supported prostheses. However, milling can generate considerable material waste, contribute to cutting-tool wear, and increase production costs. Furthermore, bur diameter, tool accessibility, restoration geometry, and machine configuration may limit the reproduction of fine details and complex structures. Despite these limitations, CAD/CAM milling remains an important manufacturing approach in contemporary prosthodontics because of its versatility and established clinical applications.[6-8]

Comparison of Mechanical Properties

The mechanical performance of three-dimensional (3D)-printed and milled dental prostheses depends on material composition, manufacturing parameters, internal structure, and post-processing procedures. Although milling uses industrially manufactured blocks with controlled material properties, 3D printing may introduce layer-related anisotropy, porosity, and interlayer defects that influence mechanical behavior.[1,2] However, these differences vary according to the material and manufacturing technique.

Flexural strength

represents the ability of a material to withstand bending forces before fracture. Milled ceramics, particularly zirconia and lithium disilicate, exhibit favorable flexural strength because of their established material composition and manufacturing processes. The flexural strength of printed resins and polymers depends on printing orientation, layer thickness, degree of polymerization, and post-curing conditions. Therefore, comparisons should consider equivalent material categories and standardized testing protocols.[9]

Fracture toughness and fracture resistance describe a material's ability to resist crack propagation and

Table 1

Table 1. Major Three-Dimensional Printing Systems Used in Dentistry				
3D Printing System	**Principle**	**Advantages**	**Limitations**	**Dental Applications**
Stereolithography (SLA)	UV laser selectively polymerizes liquid photosensitive resin layer by layer	High accuracy; excellent resolution; fine detail reproduction	Requires washing and post-curing; support structures may be required	Diagnostic models, surgical guides, denture bases, provisional restorations, occlusal splints
Digital Light Processing (DLP)	Projected light polymerizes an entire resin layer simultaneously	Faster printing; good accuracy; suitable for batch production	Material and printer dependent; post-processing required	Denture bases, surgical guides, provisional restorations, occlusal appliances
LCD Printing	UV light passes through an LCD screen to selectively polymerize resin	Good resolution; relatively low equipment cost; rapid fabrication	LCD components have limited lifespan; accuracy depends on exposure and resin parameters	Models, surgical guides, denture bases, provisional restorations, appliances
Fused Deposition Modeling (FDM)	Heated thermoplastic filament is extruded layer by layer	Low cost; simple operation; minimal material wastage	Lower resolution; visible layer lines; finishing may be required	Diagnostic models, prototypes, custom trays, educational models

withstand fracture under applied forces, respectively. In printed restorations, interlayer bonding, internal porosity, and manufacturing defects may act as stress-concentration sites. Milled restorations fabricated from high-quality ceramic blocks may exhibit predictable fracture behavior, although flaws introduced during machining, surface finishing, or subsequent processing can also affect their performance. Fracture behavior is influenced by material composition, restoration thickness, geometry, and loading conditions.[1]

Compressive strength refers to the ability of a material to resist deformation or failure under compressive forces. This property is important in prostheses exposed to substantial occlusal loading. Milled ceramics and resin-based materials demonstrate material-dependent compressive performance, while printed materials may exhibit variations associated with build orientation, porosity, and polymerization. Compressive strength alone, however, cannot reliably predict the clinical longevity of a restoration.

Hardness measures resistance to localized indentation or surface penetration. It influences the surface durability of dental materials and may affect their susceptibility to scratching and abrasion. Milled ceramics generally demonstrate high hardness, whereas printed polymer-based materials exhibit properties determined by resin formulation and polymerization. Surface finishing, polishing, and post-processing may further influence the measured hardness of both printed and milled restorations.

Elastic modulus describes a material's stiffness and its resistance to elastic deformation under applied stress. Materials with a higher elastic modulus are generally stiffer, whereas those with a lower modulus exhibit greater elastic deformation. Milled ceramics typically possess a higher elastic modulus than polymer-based materials. In printed materials, the modulus may vary with printing orientation, layer adhesion, and degree of conversion. The clinical significance of these differences depends on restoration geometry, material thickness, and the distribution of occlusal forces.

Fatigue resistance refers to the ability of a material to withstand repeated loading without developing progressive damage or fracture. Dental restorations experience repeated mechanical stresses during mastication, making fatigue performance important for long-term service. Printed materials may be susceptible to fatigue damage associated with interlayer defects and internal porosity, whereas milled restorations may benefit from the relatively uniform structure of prefabricated materials. Nevertheless, fatigue resistance varies substantially with material composition, surface defects, environmental conditions, and manufacturing protocols.[10,11]

Wear resistance represents the ability of a material to withstand progressive material loss caused by contact and friction. This property is important for maintaining occlusal anatomy and minimizing wear of opposing dentition. Milled ceramics often demonstrate favorable wear resistance, although their surface roughness and hardness can influence wear of opposing teeth. Printed resins may exhibit different wear characteristics depending on filler content, polymerization, sur-

face finishing, and the material used for comparison. Appropriate polishing and finishing are important for both manufacturing approaches.[11]

Bond strength describes the ability of an adhesive interface to resist separation between a restoration and a bonding substrate. It is influenced by surface composition, roughness, surface treatment, adhesive systems, and the type of restorative material. Milled ceramics may require material-specific treatments, such as hydrofluoric acid etching and silanization for suitable silica-based ceramics or air abrasion and appropriate primers for zirconia. Printed resin-based restorations may require cleaning, surface conditioning, and compatible bonding agents according to the manufacturer's instructions. Differences in bond strength should therefore be interpreted in relation to the material and bonding protocol rather than manufacturing method alone.[1]

Resistance to cyclic loading refers to the ability of a restoration to withstand repeated loading and unloading without developing excessive deformation, cracking, or structural failure. Although closely related to fatigue resistance, cyclic loading evaluates performance under repeated loading conditions that may simulate aspects of mastication. Factors such as restoration thickness, geometry, support, internal defects, and load magnitude influence performance. Both printed and milled restorations require standardized cyclic-loading assessments to determine their durability under clinically relevant conditions.[1]

Overall, the mechanical properties of 3D-printed and milled prosthodontic materials are influenced by several interacting factors, and neither manufacturing technique demonstrates universal superiority across all material categories and clinical applications. Meaningful comparisons require standardized testing, material-specific analysis, and consideration of clinical variables. Further long-term studies are needed to establish how differences in laboratory mechanical performance translate into restoration survival and clinical success.[1,10]

Clinical Applications in Prosthodontics

Three-dimensional printing and CAD/CAM milling are increasingly used in prosthodontics for the fabrication of crowns, fixed dental prostheses, removable dentures, implant-supported restorations, provisional restorations, surgical guides, and diagnostic models. Milling is well established for producing definitive restorations from materials such as zirconia, lithium disilicate, and resin-matrix ceramics, whereas 3D printing offers flexibility in manufacturing complex geometries and customized components. In implant prosthodontics, digital workflows integrate intraoral scanning, computer-aided design, and computer-aided manufacturing to improve communication, streamline treatment planning, and support the fabrication of implant-supported prostheses. The clinical suitability of either technique depends on the restorative material, the type of prosthesis, dimensional accuracy, mechanical requirements, esthetic expectations, and available equipment. Although both approaches can provide clinically acceptable outcomes, their performance should be assessed for each specific application rather than assuming that one manufacturing method is universally superior.[11,12]

Manufacturing Efficiency and Economic Considerations

: Manufacturing efficiency and cost are important factors when selecting between three-dimensional printing and CAD/CAM milling in prosthodontics. Three-dimensional printing builds restorations layer by layer, potentially reducing material wastage and allowing multiple components to be fabricated simultaneously within a single build. This approach may be advantageous for producing models, provisional restorations, denture components, and other customized devices. However, the overall workflow may require additional steps, including support removal, washing, post-curing, and finishing, which influence production time and labor requirements. Milling generally provides a predictable workflow for fabricating restorations from prefabricated industrially manufactured blocks or discs. Nevertheless, it can generate considerable material waste, particularly when milling restorations from expensive ceramic blocks, and requires periodic replacement of milling burs and maintenance of the equipment.

The economic feasibility of either technique depends on equipment acquisition costs, material expenses, maintenance, technician expertise, production volume, and the time required to complete each restoration. Although 3D printing may offer advantages in batch production and material utilization, these benefits can be offset by post-processing requirements and the cost of validated materials. Milling may be more suitable for laboratories with established CAD/CAM infrastructure and a consistent demand for definitive ceramic restorations. Therefore, a comprehensive economic assessment should consider the entire manufacturing workflow, including labor, consumables, equipment depreciation, remakes, and clinical adjustments, rather than comparing material costs alone. Further studies incorporating standardized cost analyses and clinical outcome data are needed to establish the relative

cost-effectiveness of these technologies across different prosthodontic applications.[11,12]

Limitations and Challenges

Despite significant advances in digital manufacturing, three-dimensional (3D) printing and computer-aided design/computer-aided manufacturing (CAD/CAM) milling have several limitations that may influence their clinical application in prosthodontics. The accuracy and mechanical performance of printed restorations depend on factors such as printing technology, build orientation, layer thickness, material composition, and post-processing protocols. Inadequate polymerization or inappropriate processing may affect dimensional stability, surface characteristics, and mechanical strength. Milling, although widely established, is associated with material wastage, instrument wear, restricted access to intricate geometries, and potential marginal discrepancies. Both approaches require appropriate digital equipment, trained personnel, and standardized manufacturing protocols. Differences in testing methods, material formulations, and study designs also make direct comparisons between the two technologies difficult. Furthermore, evidence regarding long-term clinical survival, wear behavior, fatigue resistance, and biological responses remains limited for several additively manufactured prosthodontic materials. Consequently, material selection and manufacturing methods should be guided by the intended clinical application, validated material properties, and available scientific evidence.[13-15]

Future Perspectives

Future developments in digital prosthodontics are expected to improve the accuracy, efficiency, and clinical reliability of both 3D printing and CAD/CAM milling. Advances in printable ceramic materials, high-performance polymers, and composite resins may expand the range of restorations that can be manufactured additively. Improvements in printing resolution, automated post-processing, and quality-control systems could further enhance dimensional accuracy and reproducibility. Similarly, advancements in milling equipment, cutting tools, and software algorithms may improve manufacturing precision while reducing processing time and material waste. Integration of artificial intelligence into digital design and manufacturing workflows may facilitate automated restoration design, defect detection, and process optimization. Hybrid manufacturing approaches that combine printing and milling may also offer opportunities to utilize the advantages of both techniques. However, future research should prioritize standardized comparative studies, long-term clinical trials, and cost-effectiveness analyses to establish the indications and limitations of each approach. Greater consistency in reporting material characteristics, manufacturing parameters, and clinical outcomes will be essential for translating technological advances into predictable patient care.

CONCLUSION

Three-dimensional printing and CAD/CAM milling represent complementary manufacturing approaches in contemporary prosthodontics. Milling remains an established option for producing definitive restorations from validated ceramic and resin-based materials, whereas 3D printing offers flexibility in design, customization, and the fabrication of complex structures with potentially reduced material wastage. However, neither technique demonstrates universal superiority across all prosthodontic applications. Their clinical performance depends on material selection, manufacturing parameters, dimensional accuracy, mechanical properties, and post-processing procedures. Although digital technologies continue to expand treatment possibilities, further standardized investigations and long-term clinical studies are required to clarify their comparative effectiveness, durability, and economic feasibility. An application-specific approach that considers clinical requirements, material characteristics, and available evidence will support the appropriate integration of both technologies into prosthodontic practice.

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