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Dentistry

ADVANCED PRINTING TECHNOLOGIES IN PROSTHODONTICS: A SCOPING REVIEW ON 3D TO 6D INNOVATION.

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ABSTRACT Advances in digital technologies are revolutionizing prosthodontics, with 3D, 4D, and 5D printing leading the charge in redefining the precision and personalization of dental prosthetics. While 3D printing has established itself as a cornerstone for creating crowns, bridges, and dentures with exceptional accuracy and efficiency, the advent of 4D printing introduces dynamic adaptability through smart materials responsive to environmental stimuli. Building on this, 5D printing incorporates motion and real-time interaction, allowing prosthetic devices to dynamically adjust to oral functions like chewing and speaking. The potential of 6D printing takes these innovations further by embedding real-time feedback mechanisms, enabling prostheses to autonomously adapt to oral changes, enhancing durability and patient comfort. This review explores the principles, clinical applications, and challenges of these transformative technologies, highlighting their potential to redefine dental care through enhanced functionality, longevity, and customization. Together, 4D, 5D, and 6D printing promise to revolutionize prosthodontics, paving the way for intelligent, adaptive, and patient-specific dental solutions.

KEYWORDS : 3D /4Dprinting ,5D printing,6D printing, additive manufacturing, smart materials

INTRODUCTION

The evolution of digital technologies in the dental field has ushered in a new era of precision, customization, and efficiency in prosthodontics.[1] From 3D printing to the more advanced concepts of 4D, 5D, and 6D printing, these technologies are transforming the way dental professionals design, manufacture, and deliver prosthetic devices.[2] Prosthodontics, which focuses on restoring and replacing damaged or missing teeth, has seen significant changes through the integration of additive manufacturing technologies, particularly 3D printing.[3] This revolution has already enabled faster production of prostheses, customized solutions, and increased accuracy in fitting.[4] However, the next frontier lies in the application of 4D, 5D, and 6D printing, which promise to add even more sophistication and functionality to prosthodontic care.

4D printing refers to the ability of an object to change shape or characteristics in response to external stimuli such as temperature, light, or pressure over time. Unlike traditional 3D printed objects, which are static, 4D-printed prostheses are made from smart materials capable of self-adjustment. This capability opens new possibilities in creating dental restorations that can adapt to the changing conditions inside the mouth, such as temperature fluctuations or slight changes in the shape of the gingiva and bones.[5,6,7]

Building on the potential of 4D printing, 5D printing adds the dimension of motion or dynamic interaction. While 3D printing builds objects layer by layer, and 4D printing incorporates time as a dimension, 5D printing introduces real-time changes in the printed object's behavior. This enables the creation of prostheses that can interact with the patient's oral environment. In prosthodontics, a 5D-printed dental implant or denture could adjust its rigidity and flexibility according to the patient's biting forces or the way the jaw moves during speaking or eating. This dynamic adjustment can improve comfort, durability, and functionality, offering a truly personalized and responsive prosthesis.[7,8,9]

6D printing extends the concept even further, integrating time, motion, and real-time environmental feedback. Though still an emerging technology, 6D printing promises to create highly interactive prosthetic devices that respond not just to external stimuli, but also to internal factors such as pressure points or temperature variations within the mouth. This could lead to prostheses that automatically optimize their performance based on the wearer's bite, reducing discomfort, preventing damage, and ensuring long-lasting function. The concept of real-time feedback in 6D printing can open avenues for creating dental restorations that autonomously adjust to the user's specific needs, responding to daily usage, aging, or changes in the oral cavity.[10,11,12]

Together, 4D, 5D, and 6D printing are setting the stage for a paradigm shift in prosthodontics, allowing for the creation of highly adaptive, long-lasting, and functional prosthetic devices. These advanced printing technologies promise not only to enhance the quality of life for patients through improved comfort and performance but also to reduce the need for frequent dental visits, adjustments, and repairs.[13] As the research and development in these fields continue, these printing technologies hold the potential to radically reshape how prosthodontic care is delivered, paving the way for a new era of personalized, interactive, and self-adjusting dental restorations.

In the following sections, we will explore the principles, potential applications, and challenges of 4D, 5D, and 6D printing in prosthodontics, offering a comprehensive review of their current impact and future prospects in the dental field

Technological Advancements Of 4d, 5d, And 6d Printing

Advancements in 4D, 5D, and 6D printing represent a paradigm shift in additive manufacturing. Each build on traditional 3D printing but introduces additional dimensions for dynamic functionality, adaptability, and interactivity.[14]

4D printing leverages smart materials like shape-memory polymers (SMPs), hydrogels, and self-healing materials. SMPs can adjust shape with temperature changes, while hydrogels adapt to moisture, ensuring better fit and comfort. Self-healing materials enable prostheses to repair minor damage autonomously, reducing replacement frequency and enhancing longevity.[14]

5D printing adds real-time motion and interaction, enabling prostheses to respond dynamically to oral forces like chewing or speaking. Multi-material printing allows the creation of devices that are both rigid and flexible, improving performance during daily activities.[15]

6D printing integrates real-time feedback with motion and adaptability. Embedded sensors monitor bite pressure, temperature, and moisture, enabling prostheses to optimize fit and functionality autonomously. These innovations create highly interactive devices that continuously adjust to the patient's oral environment, ensuring precision and long-term performance.(Figure 1)(Table 1)[16]

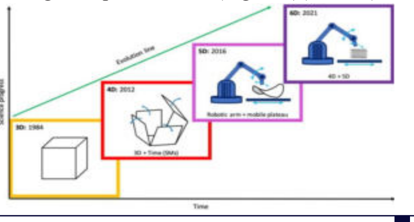

Figure 1. A schematic illustration of 3D-printing technology evolution. The chronological steps of the transformation of 3D-printing technology to the 6D-printing concept.

Table 1: Materials Used in 4D,5D and 6D Printing for Dentistry

4D printing	5D printing	6D printing
Shape-Memory Polymers (SMPs): These materials can "remember" and return to their original shape when exposed to stimuli such as heat or light. **Hydrogels**: Biocompatible and water-responsive, hydrogels are used in tissue engineering and adaptive fillings. **Electroactive Polymers**: These materials respond to electrical signals, making them ideal for dynamic orthodontic devices. **Thermo-Responsive Polymers**: These change their properties based on temperature fluctuations, useful for adaptive dentures and crowns.	**Shape-Memory Alloys (SMAs)**: These materials can withstand mechanical stress and return to their original shape when activated by stimuli like heat or light. **Biocompatible Polymers**: Used for dental implants and restorative materials, these polymers offer high durability and compatibility with oral tissues. **Hydrogels**: Ideal for regenerative scaffolds, hydrogels promote cell growth and healing.	**Smart Polymers**: Materials capable of changing properties in response to environmental stimuli such as temperature, pressure, or pH levels. **Bio-Sensors**: Embedded within dental products, these sensors monitor real-time conditions like inflammation, pressure, or bacterial activity. **Nano-Materials**: Used to enhance strength, conductivity, and responsiveness, ensuring long-term performance in dental applications. **Conductive Materials**: For powering sensors or transmitting data, these materials play a critical role in enabling intelligent functionality.

Clinical Applications Of 3d, 4d, 5d, And 6d Printing In Prosthodontics

3D printing has revolutionized prosthodontics by enabling the precise, cost-effective production of crowns, bridges, dentures, and surgical guides. It offers rapid production and reduces errors, making it a cornerstone of modern dental care.[12]

4D printing extends these benefits by incorporating materials that adapt to environmental changes like temperature and moisture, allowing prostheses to adjust over time. This enhances device longevity and reduces follow-up adjustments.[14]

5D printing introduces dynamic interaction, enabling prostheses to adjust in real time to chewing forces or jaw movements. This ensures better fit and enhanced functionality, especially in removable dentures and implant-supported prostheses.[15]

6D printing represents the future of prosthodontics, combining feedback systems with real-time adaptability. Devices can autonomously adjust to changes in bite or oral health, optimizing performance and reducing manual intervention.[16]

Challenges And Advantages

While 3D printing has limitations such as material constraints and high initial costs, it paved the way for innovations like 4D, 5D, and 6D printing.

The strengths of 4D printing lie in its smart materials, which enable prostheses to adapt to oral changes, improving fit and comfort. 5D printing adds dynamic motion, creating devices that respond to functional stresses like chewing. 6D printing integrates real-time feedback, enabling self-optimization and continuous monitoring of oral health, ensuring long-term functionality

Whereas Challenges in 4D Printing are High costs and limited material durability in harsh oral environments hinder 4D printing adoption. Its technical complexity requires specialized expertise, while lengthy regulatory processes further slow its implementation. The high initial investment and material limitations pose barriers to 5D printing. Designing advanced products demands expertise, and rigorous regulatory compliance adds to the challenges.

6D printing's complexity stems from integrating sensors, AI, and dynamic materials. High costs, strict regulatory standards, and ensuring the reliability of smart components in oral environments remain significant obstacles.[14,15,16]

Table 2: Advantages of 4D,5D and 6D Printing in Dentistry

4D printing	5D printing	6D printing
1. Enhanced Personalization 4D printing allows the creation of products tailored to individual patients. By using patient-specific data, such as 3D scans of the oral cavity, the products are designed to fit perfectly and adapt over time. **2. Improved Efficiency** The adaptive nature of 4D-printed products reduces the need for frequent adjustments and replacements, saving time for both patients and dental professionals. **3. Greater Comfort and Functionality** Products like self-adjusting braces and adaptive dentures ensure a comfortable fit, even as the patient's oral structures change. **4. Reduced Waste** The precise nature of 4D printing minimizes material wastage, making it an environmentally friendly option. **5. Innovative Treatment Options** From dynamic orthodontic devices to regenerative scaffolds, 4D printing opens new avenues for advanced dental treatments.	**1. Superior Precision** 5D printing's multi-axis capabilities allow the production of dental products with exceptional accuracy, reducing the need for post-processing and ensuring a perfect fit. **2. Enhanced Structural Integrity** Products manufactured through 5D printing are inherently stronger, as the additional axes reduce stress concentrations and weak points. **3. Greater Efficiency** 5D printing minimizes waste by optimizing material usage and streamlining the manufacturing process, making it more cost-effective in the long run. **4. Advanced Adaptability** Dental products produced via 5D printing can adapt dynamically to the patient's oral environment, enhancing comfort and functionality. **5. Personalized Solutions** By leveraging patient-specific data, 5D printing ensures that every product is uniquely tailored to individual needs.	**1. Real-Time Adaptability** 6D printing products can monitor and respond to environmental changes, ensuring optimal functionality and patient comfort over time. **2. Enhanced Precision and Feedback** By incorporating sensors and AI, 6D-printed dental products provide detailed feedback to dentists, improving diagnostic accuracy and treatment outcomes. **3. Longer Lifespan** Self-healing and adaptive properties extend the durability of dental products, reducing the need for replacements or repairs. **4. Improved Patient Care** Products tailored to the patient's ongoing oral health conditions offer unparalleled customization and effectiveness. **5. Integration with Smart Devices** 6D-printed products can connect to smartphones or other devices, enabling remote monitoring and timely interventions.

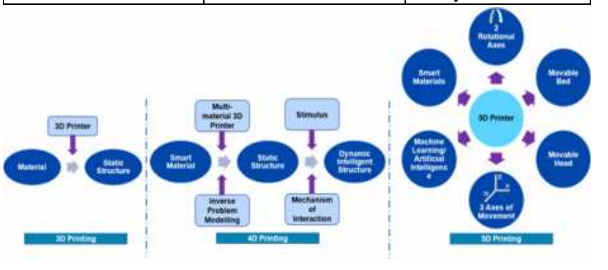

Figure 2. Difference between 3D, 4D and 5D printing techniques used in dentistry

Future Potential

The future potential of 4D, 5D, and 6D printing in dentistry is vast, driven by innovations that promise to revolutionize dental care through enhanced adaptability, precision, and efficiency. In 4D printing, advancements such as bioprinting entire teeth using stem cells and bioengineered materials could enable teeth to grow and adapt like natural ones, while integration with AI and robotics may bring unmatched precision and scalability.[14] Similarly, 5D printing is poised to transform dentistry with dynamic orthodontic devices, self-adjusting braces, and fully bioprinted teeth that replicate natural functionality, supported by AI-driven design processes and reduced costs making these innovations more accessible.[15] The possibilities extend even further with 6D printing, where interactive dental ecosystems, energy-harvesting technologies, and robotic integration could create highly intelligent and adaptive dental devices, revolutionizing treatment strategies and offering real-time interaction between tools and systems.[16] Together, these advancements hold the potential to redefine the future of dentistry, improving outcomes, reducing costs, and enhancing patient care.

CONCLUSION

Advancements in 4D, 5D, and 6D printing are transforming prosthodontics by offering highly customizable, adaptive, and intelligent dental solutions. These technologies enhance patient comfort, reduce the need for frequent adjustments, and provide long-term personalized care, paving the way for the next generation of prosthodontic innovations.

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