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Advancing Dental Care with Soft Robotics: Materials, Applications, and Future Directions

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Abstract

The rapidly developing field of soft robotics uses bioinspired, flexible, and compliant materials to create robotic devices that may safely and adaptably interact with biological tissues. In contrast to conventional rigid robots, they emulate the characteristics of human muscles, tendons, and tissues. Soft robotics offers promising options for automation, minimally invasive procedures, and improved prosthodontic treatments that focuses on improving the comfort, adaptability, and functionality of dental and prosthetic devices.

Historically, rigid mechanical devices intended for automated milling and implant insertion have been the main focus of robotics integration in dentistry. However, the flexibility and biocompatibility of these systems are limited. By utilizing materials like shape-memory polymers, elastomers, and bio-hydrogels, soft robotics enables more delicate and accurate interactions with oral tissues. The goal of this review is to investigate recent breakthroughs in soft robotic technology for dental applications, analyse current challenges and evaluate future outlooks in the field.

Keywords: robotic devices, soft robots, soft material, bio-inspired robotics

INTRODUCTION

In the natural world, many organisms possess body structures that allow them to thrive in ever-changing and challenging surroundings. Their morphological traits and mechanical responsiveness enable quick adaptation and interaction with their environments. These traits—such as flexibility, compliance, and variable stiffness—are commonly seen in biological tissues and offer insights into robotic innovation. Soft robotics seeks to replicate these features by designing systems using smart, adaptable materials that can function safely and efficiently in human-centered tasks.1

The emergence of self-healing soft robotics began in 2017 with the invention of a gripper composed of thermoreversible elastomeric material. Since then, the field has seen various approaches aimed at enabling recovery from damage. These methods include internal mechanisms like hydrogen bonding, disulfide bridges, and Diels–Alder linkages, as well as external techniques such as UV-curable healing agents. These innovations allow soft robots to repair structural cuts and maintain performance.2

Key Components of Soft Robotics

Soft Actuators

Soft actuators serve as the primary means of generating movement in soft robotic systems. Unlike rigid actuators, they allow for safe, flexible interaction with biological structures. In dental contexts, common types include Pneumatic Artificial Muscles3 (PAMs), which replicate natural muscle behavior through inflation; Shape-Memory Alloys4 (SMAs), which revert to original shapes when heated and are suitable for compact oral applications; and Dielectric Elastomer Actuators[5] (DEAs), which deform under electric fields and can support dynamic prosthetic motion.

Flexible and Biocompatible Materials

The structure of soft robots in dentistry is composed of materials that are adaptable to the anatomical complexities of the oral cavity. Silicone elastomers6 are widely used due to their moldability and compatibility with oral tissues. Hydrogels7 provide moisture retention and responsiveness to stimuli, making them ideal for regenerative applications. Additionally, biohybrid materials[8] blend synthetic polymers with biological tissue characteristics to enhance integration and performance.

Sensors and Feedback Mechanisms

Accurate feedback systems are essential for real-time adaptability in soft dental robots. Strain sensors9 track deformation and help optimize prosthetic alignment. Capacitive and resistive sensors10 monitor pressure and contact force, crucial during bite adjustments. Optical and ultrasound sensors[11] are employed to monitor device positioning and guide intraoral procedures with precision.

Control Systems and AI Integration

To enhance autonomy, soft robotics systems incorporate artificial intelligence12. These controllers interpret signals from sensors and adjust outputs to meet procedural demands. Haptic feedback13 modules allow clinicians to feel interactions, which is especially beneficial in surgery. Wireless interfaces[14] enable remote monitoring and adjustments, enhancing the versatility of intraoral robotics.

Power Supply and Energy Management

Powering soft robotic systems in constrained spaces such as the oral cavity requires compact and efficient solutions. Thin-film batteries15 are often integrated into prostheses to deliver consistent energy. Wireless power transfer[16] technology is also gaining popularity, allowing these devices to be charged externally without removal.

Biomaterials Used in Soft Robotics

1. Silicone Elastomers

Silicone-based materials are widely used in soft robotics due to their excellent flexibility, biocompatibility, and ease of processing. They can endure repeated deformation, are chemically inert, and resist degradation in moist environments. In dental applications, silicone elastomers are often utilized for fabricating shape-adaptive maxillofacial prostheses and soft liners for obturators[17].

2. Hydrogels

Hydrogels are three-dimensional polymer networks capable of absorbing large amounts of water. Their softness and tunable mechanical properties make them ideal for use in intraoral scaffolds and prosthetic liners. Certain smart hydrogels can respond to external stimuli such as pH, temperature, or pressure, adapting to dynamic changes in the oral environment[18].

3. Polyurethane Composites

Polyurethane-based materials offer high elasticity and can be customized for various hardness levels.

They are often used in components requiring high fatigue resistance and have been explored in prosthetic joint cushions and adaptive pressure-distribution systems[19].

4. Biohybrid Materials

Biohybrid materials integrate biological tissues or molecules with synthetic polymers. These materials aim to achieve natural biomechanical function and tissue compatibility. They are currently being investigated for use in self-healing intraoral prostheses and tissue-integrated scaffolds for maxillofacial reconstruction[20].

5. Shape-Memory Polymers (SMPs)

SMPs can return to a pre-defined shape in response to a specific stimulus such as heat or light. These materials are being used to create prosthetic devices that adapt their form intraorally based on temperature or mechanical stress. This is particularly advantageous in cases of post-operative tissue remodeling[21].

6. Biodegradable Polymers

Biodegradable options such as polylactic acid (PLA) and polycaprolactone (PCL) are used in temporary scaffolds and devices intended to degrade after completing their function. They are promising for applications in tissue engineering and regenerative procedures in dental and maxillofacial contexts[22].

Applications of Soft Robotics in Dentistry

1. Adaptive Maxillofacial Prostheses

Soft robotics has revolutionized facial prosthetics by introducing dynamic materials that mimic natural tissue motion. These adaptive prostheses, constructed with shape-memory polymers or silicone-based actuators, respond to thermal or mechanical stimuli. They offer enhanced retention, comfort, and expression-matching in patients with facial deformities or surgical resections[23].

2. Self-Regulating Dentures and Obturators

Soft robotics enables the creation of intelligent prosthodontic devices such as self-adjusting dentures and palatal obturators. These systems accommodate changes in mucosal topography over time, providing sustained comfort and minimizing the need for frequent relining. Soft sensors embedded within the denture base can detect load distribution and modify contact surfaces accordingly[24].

3. Intraoral Assistive Devices

Miniaturized soft robotic tools have emerged as valuable adjuncts during restorative and surgical procedures. Flexible intraoral retractors and suction devices made of elastomeric components conform to delicate oral tissues while maintaining consistent retraction or isolation. These tools reduce patient discomfort and improve surgical precision in confined spaces[25].

4. Regenerative Dental Applications

Hydrogel-based soft scaffolds integrated with drug reservoirs or stem cells are being investigated for tissue engineering in periodontal and alveolar ridge augmentation. These scaffolds can adapt to complex defects and provide controlled delivery of bioactive molecules to enhance regeneration[26].

5. Robotic Occlusal Splints and Tongue Prostheses

Soft robotic splints are designed to respond to mandibular movements, especially in patients with temporomandibular joint disorders. Likewise, robotic tongue prostheses made from responsive polymers assist in improving articulation and deglutition in hemiglossectomy patients[27].

Future Projections of Soft Robotics in Dentistry

1. Personalized Adaptive Prosthetics

The integration of artificial intelligence with soft robotics is expected to enable the fabrication of prostheses that automatically adapt to intraoral conditions. These devices may respond to variations in saliva pH, temperature, and muscular dynamics, providing tailored support and comfort for each patient[28].

2. Autonomous Intraoral Robots

Miniaturized robots capable of performing simple tasks autonomously inside the oral cavity—such as irrigation, plaque removal, or drug delivery—are under development. These robots will be able to navigate dynamic environments without continuous human control, revolutionizing preventive dental care[29].

3. 4D Printed Responsive Devices

4D printing, which allows materials to change shape or behavior over time, will likely enhance the design of dynamic oral appliances. Such devices could shift morphology in response to mechanical loading or healing processes, improving long-term patient outcomes[30].

4. Integration with Regenerative Therapies

Soft robotic scaffolds integrated with bioactive agents, stem cells, or growth factors will be used for real-time modulation of the healing environment. These systems could actively guide bone or soft tissue regeneration, especially in complex oral defects[31].

5. Tele-dentistry and Remote Adjustments

With the advancement of IoT and wireless technologies, future soft robotic prostheses may allow real-time monitoring and remote calibration. This would be particularly beneficial for patients in rural or underserved areas, improving continuity of care[32].

Advantages and Challenges of Soft Robotics in Dentistry

Advantages

1. Enhanced Patient Comfort: Soft robotic components adapt better to the oral environment, reducing irritation and enhancing comfort during prolonged prosthesis wear[33].
2. Tissue Compatibility: The use of biocompatible materials minimizes adverse reactions and promotes better integration with surrounding tissues[34].
3. Customizability: Soft robotic systems can be tailored to suit individual anatomical and functional needs, especially in prosthodontic applications[35].
4. Precision and Safety: Embedded sensors and feedback mechanisms allow real-time adjustments, improving procedural accuracy and minimizing trauma[36].
5. Regenerative Integration: Soft robotic scaffolds facilitate cell growth and healing, enhancing the potential of tissue engineering in oral rehabilitation[37].

Challenges and Limitations

1. Power and Energy Supply: Maintaining sufficient and stable energy delivery in confined oral spaces remains a technological hurdle[38].
2. Durability and Fatigue Resistance: Soft robotic materials often degrade over time due to moisture, mastication forces, and temperature fluctuations[39].
3. Cost and Accessibility: High fabrication and material costs may limit widespread clinical adoption,

especially in resource-limited settings[40].

4. Sterilization and Hygiene: Many soft materials are not compatible with conventional sterilization processes, raising concerns about cross-contamination[41].
5. Regulatory and Ethical Issues: Lack of standardized guidelines and long-term clinical trials creates uncertainty in regulation, approval, and patient acceptance[42].

Conclusion

Soft robotics represents a transformative shift in the landscape of dental and maxillofacial rehabilitation. Its integration into clinical dentistry promises improved patient-specific solutions, enhanced comfort, and greater procedural precision. Through the use of biocompatible, flexible materials and smart sensing systems, soft robotic devices are beginning to replace or augment traditional prosthodontic tools and therapeutic protocols. Applications ranging from adaptive prostheses and regenerative scaffolds to autonomous intraoral tools are already showing immense potential in experimental and early clinical settings. Despite the significant advantages, current limitations such as energy delivery, sterilization, and regulatory clarity must be addressed before widespread clinical adoption becomes feasible. Continued interdisciplinary collaboration and robust clinical research will be essential to harness the full potential of soft robotics in dentistry. As materials science, artificial intelligence, and biomedical engineering evolve, the role of soft robotics in dentistry is set to expand rapidly, offering new hope and functionality for patients worldwide.

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