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ANALYSIS OF 4D PRINTING IN HEALTHCARE

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Abstract – 4D printing has emerged as a transformative technology in the field of biomedical engineering, offering the potential for dynamic, stimuli-responsive structures with applications in tissue engineering, drug delivery, medical devices, and diagnostics. This review paper provides a comprehensive analysis of the advancements, challenges, and future directions of 4D printing in biomedical engineering. We discuss the development of smart materials, including stimuli-responsive polymers, shape-memory materials, and bio-inks, as well as the various fabrication techniques employed, such as direct-write assembly, stereolithography, and multi-material jetting. Despite the promising advances, several challenges persist, including material limitations related to biocompatibility, mechanical properties, and degradation rates; fabrication complexities arising from the integration of multiple materials, resolution and accuracy, and scalability; and regulatory and ethical considerations surrounding safety and efficacy. As we explore the future directions for 4D printing, we emphasise the need for material innovations, fabrication advancements, and emerging applications such as personalised medicine, nanomedicine, and bioelectronic devices. Interdisciplinary research and collaboration between material science, biology, engineering, regulatory agencies, and industry are essential for overcoming challenges and realising the full potential of 4D printing in the biomedical engineering landscape.

Keywords: 4D printing; biocompatibility; biomedical engineering; fabrication techniques; smart materials.

1. INTRODUCTION

The advent of 3D printing technology has transformed various fields, including biomedical engineering, by allowing the fabrication of complex structures with high precision and accuracy [1]. Over the years, 3D printing has been employed to create patient-specific implants, prosthetics, and even living tissue constructs for regenerative medicine [2–5]. However, these static structures lack the dynamic functionality needed to mimic the behaviour of living systems. The emergence of 4D printing, a technology that combines 3D printing with smart materials that can change shape or properties over time in response to external stimuli, has opened new possibilities for creating dynamic structures in biomedical engineering. 4D printing technology incorporates stimuli-responsive materials, such as shape-memory polymers, hydrogels, and bio-inks, into the printing process to create structures capable of transforming under specific conditions, such as changes in temperature, pH, or moisture [6,7]. These dynamic materials enable the design of advanced biomedical devices that can adapt to the physiological environment, leading to improved therapeutic outcomes and patient-specific treatments.

1.1. Brief Overview of 3D Printing in Biomedical Engineering

3D printing, also known as additive manufacturing, has become an indispensable tool in the field of biomedical engineering over the past few decades. This technology allows for the creation of three-dimensional objects by depositing materials layer-by-layer based on a digital model [8,9]. The versatility of 3D printing has led to its widespread adoption in various biomedical applications, from patient-specific implants and prosthetics to tissue engineering and drug delivery systems. One significant application of 3D printing in biomedical engineering is the fabrication of patient-specific implants and prosthetics [10].

1.2. Definition of 4D Printing

4D printing is an advanced form of additive manufacturing that combines the principles of 3D printing with the use of smart materials that are capable of changing their shape, properties, or functionality over time in response to external stimuli [15]. The term "4D" refers to the fourth dimension, which is time, emphasising the dynamic behaviour of these printed structures. By incorporating stimuli-responsive materials, such as shape-memory polymers, hydrogels, and bio-ink , 4D printing technology enables the creation of dynamic structures that can adapt to their environment, offering new possibilities for biomedical applications.

The significance of 4D printing in biomedical engineering lies in its potential to transform various aspects of healthcare, including tissue engineering, drug delivery systems, medical devices, and diagnostics. The dynamic nature of 4D-printed structures allows for the development of more sophisticated and adaptive devices that can mimic the complex behaviour of living systems, ultimately improving therapeutic outcomes and enabling patient-specific treatments. For instance, in tissue engineering and regenerative medicine, 4D printing can be used to create constructs that transform into the desired shape or structure upon implantation, facilitating better integration with the surrounding tissue and promoting cell growth and differentiation.

Figure 1 shows an overview of 4D printing. which includes the stages of material selection, design, fabrication, and activation. The material selection stage involves choosing the appropriate stimuli-responsive materials that can undergo controlled shape transformations.

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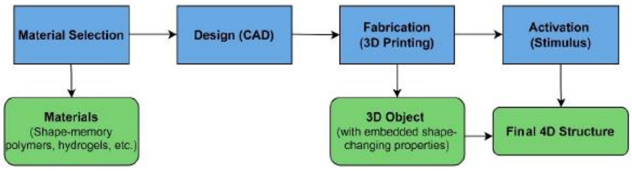

Figure 1: An overview of the 4D printing process

Table 1 compares the key features, advantages, and limitations of 3D and 4D printing technologies in the context of biomedical engineering. Overall, the advent of 4D printing technology holds significant promise for advancing the field of biomedical engineering by enabling the development of dynamic, stimuli-responsive structures that better replicate the complexity of living systems and address unmet clinical needs.

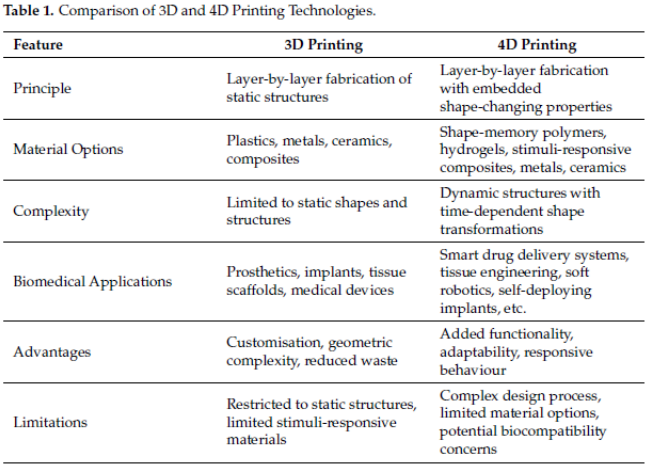

Table 1. Comparison of 3D and 4D Printing Technologies.

Feature	3D Printing	4D Printing
Principle	Layer-by-layer fabrication of static structures	Layer-by-layer fabrication with embedded shape-changing properties
Material Options	Plastics, metals, ceramics, composites	Shape-memory polymers, hydrogels, stimuli-responsive composites, metals, ceramics
Complexity	Limited to static shapes and structures	Dynamic structures with time-dependent shape transformations
Biomedical Applications	Prosthetics, implants, tissue scaffolds, medical devices	Smart drug delivery systems, tissue engineering, soft robotics, self-deploying implants, etc.
Advantages	Customisation, geometric complexity, reduced waste	Added functionality, adaptability, responsive behaviour
Limitations	Restricted to static structures, limited stimuli-responsive materials	Complex design process, limited material options, potential biocompatibility concerns

1.3. Objectives of the Paper

The primary objective of this review paper is to provide a comprehensive and up-to date overview of the advancements, challenges, and future directions in the field of 4D printing for biomedical engineering applications. As 4D printing technology continues to evolve, it is crucial for researchers, engineers, and clinicians to understand its implications, opportunities, and limitations in the biomedical field.

2. Advancements in 4D Printing for Biomedical Applications

Over the last few years, advancements in 4D printing have significantly impacted the field of biomedical applications. This innovative technology has the potential to reshape the biomedical sector, offering promising solutions for various challenges. In the following sections, we will discuss various materials and manufacturing processes employed for 4D printing. We will then discuss an array of biomedical applications for 4D printing.

2.1. Materials and Manufacturing Techniques for 4D Printing

Materials and manufacturing techniques for 4D printing are essential for achieving the desired shape-shifting and functionality in printed objects. In 4D printing, smart materials are utilised due to their ability to change properties under specific environmental conditions or stimuli. Advanced manufacturing techniques for 4D printing enable the precise fabrication of complex, multi-material structures with tailored responses to specific stimuli. These techniques have evolved to meet the unique requirements of 4D printing, including the ability to integrate smart materials and achieve high-resolution features. A brief overview of these materials and techniques can be found in the subsequent sections.

2.1.1. Smart Materials for 4D Printing

The development of smart materials that can respond to external stimuli is a critical aspect of 4D printing in biomedical engineering. These materials enable the creation of dynamic structures capable of transforming their shape or properties in response to changes in the environment. Incorporating smart materials into 4D printing processes allows researchers to create dynamic structures with transformative potential across the healthcare field. Shape-memory polymers (SMPs) are one example of smart materials used in 4D printing. SMPs can transition between a deformed state and their original shape upon exposure to a specific stimulus, such as heat or light. This property enables the fabrication of 4D-printed structures that change their shape or configuration when subjected to the appropriate trigger. For instance, an SMP-based 4D-printed scaffold can adapt its shape to better fit the tracheal structure when exposed to body heat, potentially improving the effectiveness and precision of tracheal repair procedures.

2.1.2. Fabrication Techniques for 4D Printing

Various fabrication techniques have been adapted for 4D printing, with each method offering specific advantages and limitations depending on the materials used and the desired application. Below are the typical manufacturing processes used for 4D printing. Fused Deposition Modelling (FDM) is a widely used 3D printing technique that involves the extrusion of a thermoplastic filament through a heated nozzle, which deposits the material layer by layer to create the desired object. Figure 2 shows a schematic representation of the FDM process. In 4D printing for biomedical engineering, FDM can be used to print structures with shape-memory polymers, which can change their shape upon exposure to specific stimuli, such as heat. For example, researchers have used FDM to print customisable lattice structures for bone implants. This innovative approach enables the implant to conform to a patient's unique anatomy, which may enhance osseointegration, improve surgical outcomes, and increase patient comfort. V Stereolithography (SLA) is a 3D printing technique that uses a light source, usually a laser, to selectively cure a photosensitive resin layer by layer. A sketch of the stereolithography process is depicted in Figure 3. By incorporating smart materials into the resin, researchers can create 4D-printed structures with biomedical applications. For instance, scientists have used SLA to print hydrogels that swell or shrink in response to changes in pH, which could be used in drug delivery systems for controlled and targeted release of medications.

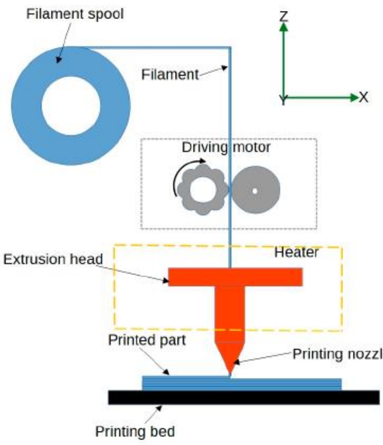

Figure 2. Schematics of the fused deposition modelling process.

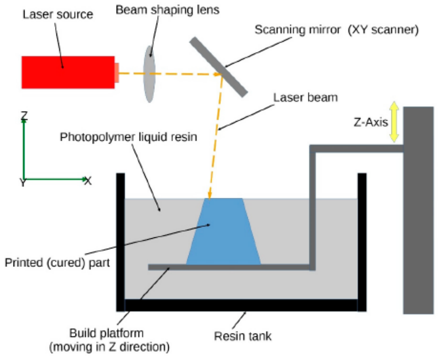

Figure 3. Schematic representation of the stereolithography process.

Digital Light Processing (DLP) is similar to SLA, but instead of using a laser, it employs a digital light projector to cure the resin. Figure 4 shows a schematic view of the DLP process. This technique can achieve higher printing speeds and finer resolution compared to SLA, making it suitable for printing intricate 4D structures in biomedical engineering.

Researchers have used DLP to create 4D-prined bioresorbable devices with near-infrared responsiveness, photothermal properties, and shape-memory functions. These innovative devices have the potential to transform various medical applications, such as drug delivery and minimally invasive surgery, by offering customisable, dynamic, and efficient solutions.

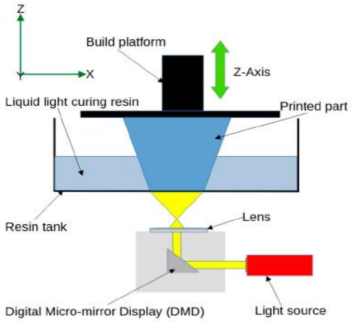

Figure 4. Schematic view of the digital light processing technique.

Selective Laser Sintering (SLS) is a powder-based 3D printing technique that uses a laser to selectively sinter or fuse powdered material layer by layer, as illustrated in Figure 5. By incorporating shape-memory polymers or other smart materials in the powder, it is possible to create 4D-printed structures for biomedical applications. For example, Multi-Material Jetting involves the simultaneous deposition of multiple materials during the printing process, allowing for the creation of 4D-printed structures with varying mechanical properties or responsiveness to stimuli. A schematic presentation of the multi-material jetting technique is shown in Figure 6. Multi-material jetting enables the fabrication of complex, multi-functional objects for biomedical applications. Researchers have used this technique to manufacture liquid–solid co-printing of multi-material 3D fluidic devices with potential biomedical applications such as microfluidic devices or lab-on-a-chip systems.

Direct Ink Writing (DIW) is an extrusion-based printing technique that involves the deposition of a viscous ink, often containing particles or fibres, to create the desired structure. A schematic view of the DIW process is shown in Figure 7. In 4D printing for biomedical applications, DIW can be used to print structures using bio-inks containing living cells, enabling the fabrication of functional tissue constructs for regenerative medicine and tissue engineering. For example, scientists have used DIW-based 4D printing to fabricate smart hydrogel scaffolds that can undergo controlled shape transformations in response to specific environmental stimuli. This approach has the potential to enhance the fabrication of patient-specific implants, improving patient outcomes, and advancing the fields of drug delivery and minimally invasive surgery.

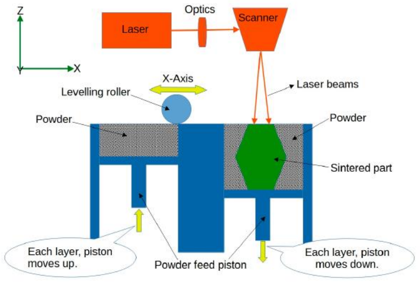

Figure 5. Sketch of the selective laser sintering process.

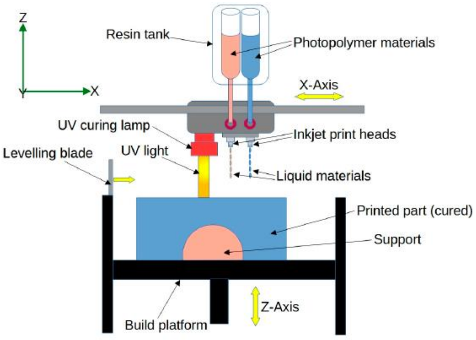

Figure 6. Schematic of the multi-material jetting process.

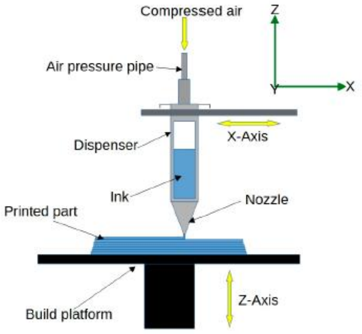

Figure 7. Schematic representation of the direct ink writing process.

2.2. Applications of 4D Printing in Biomedical Engineering

Figure 8 serves as a visual summary of the various biomedical applications of 4D printing technology that will be thoroughly discussed in the subsequent sections, offering a comprehensive overview of the potential impact of this technology on the future of healthcare.

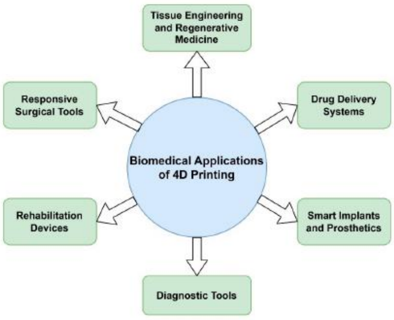

Figure 8. Selected biomedical applications of 4D printing.

2.2.1. Smart Implants and Prosthetics

The emergence of 4D printing technology has brought about remarkable progress in the creation of smart implants and prosthetics. By adding the element of time as the fourth dimension, 4D-printed devices can self-transform or adapt in response to specific stimuli, such as temperature, light, moisture, or magnetic fields. This unique attribute has led to a significant shift in the field of biomedical engineering, particularly in the design and fabrication of customisable and adaptable implants and prosthetics.

2.2.2. Drug Delivery Systems

4D printing technology has demonstrated remarkable potential in the development of advanced drug delivery systems. These systems offer significant advantages over traditional methods, including controlled release of medication, patient-specific dosing, and targeted delivery, ultimately leading to improved treatment outcomes and patient experiences.

2.2.3.Tissue Engineering and Regenerative Medicine

4D printing technology has shown immense promise in the fields of tissue engineering and regenerative medicine. By incorporating living cells into bio-inks and leveraging the unique capabilities of 4D printing, researchers have been able to create structures that can transform and develop into functional tissue over time. This ground-breaking approach has the potential to transform organ transplantation and promote faster healing for damaged tissues.

2.2.4. Responsive Surgical Tools

4D printing technology has shown immense potential in the development of responsive surgical tools that can adapt to changes in their environment, providing surgeons with greater precision and control during complex procedures. By leveraging the unique properties of 4D-printed materials, these innovative tools can adjust their shape and stiffness in response to specific stimuli, leading to improved surgical outcomes and reduced recovery times for patients.

2.2.5. Diagnostic Tools

4D printing technology has shown great potential in the development of advanced diagnostic tools that can revolution is the field of medical diagnostics. By leveraging the unique properties of 4D-printed materials, which can change their shape or properties in response to specific stimuli, researchers can create diagnostic devices that are more sensitive, accurate, and patient-specific, ultimately leading to improved patient care and outcomes.

2.2.6. Rehabilitation Devices

The advent of 4D printing technology has brought about a paradigm shift in the field of biomedical rehabilitation, introducing a new dimension of possibilities for creating adaptive, responsive, and smart devices. This new approach has the potential to redefine the design, manufacturing, and application of biomedical rehabilitation devices, making them more personalised, efficient, and comfortable for patients.

3. Challenges in 4D Printing for Biomedical Engineering

Despite the significant advancements in 4D printing for biomedical applications, several challenges remain to be addressed before the widespread adoption and implementation of this technology in clinical settings.

3.1. Materials Limitations

3.1.1. Material Properties

The performance of 4D-printed biomedical devices and structures is heavily dependent on the materials used. Smart materials, such as shape-memory polymers, hydrogels, and stimuli-responsive materials, need to exhibit the desired behaviour and response to external stimuli to fulfill their intended function. However, finding materials with the appropriate properties can be challenging. The mechanical properties, such as strength, flexibility, and durability, of these materials may not always meet the requirements for specific biomedical applications. Additionally, it is often difficult to combine multiple smart materials in a single 4D-printed structure, limiting the range of functionalities that can be achieved. Furthermore, the 4D printing process can also impose constraints on the materials used. For instance, some fabrication techniques require materials to withstand high temperatures, mechanical stress, or exposure to light or chemicals during the printing process. These factors can limit the range of materials available for 4D printing in biomedical applications.

3.1.2. Biocompatibility

Biocompatibility is a critical consideration in biomedical engineering, as the materials used must be non-toxic and non-immunogenic to ensure the safety of patients. This requirement can further limit the choice of materials for 4D printing. The development of biocompatible smart materials is still an ongoing area of research, and it can be challenging to find materials that not only exhibit the desired shape-changing behaviour, but also comply with the stringent biocompatibility requirements. Moreover, the processing techniques used in 4D printing can also affect the biocompatibility of the final product. For example, some fabrication methods may leave residual chemicals or particles that could cause adverse reactions in patients. Ensuring that the 4D printing process does not compromise the biocompatibility of the printed structure is crucial for successful implementation in biomedical applications.

3.1.3. Degradation Rate

The degradation rate of 4D-printed biomedical devices is a significant concern, particularly in applications such as drug delivery systems, tissue engineering, and implantable devices. The materials used in these applications should degrade at an appropriate rate, allowing the device or structure to perform its intended function without causing harm to the patient. For example, in drug delivery systems, the degradation rate should be controlled to ensure the proper release of the therapeutic agent over a specific period [15]. In tissue engineering, the scaffold material should degrade at a rate that matches the growth and development of new tissue. However, achieving the desired degradation rate can be challenging due to the complex interactions between the material, the fabrication process, and the biological environment. Factors such as material composition, structure, and processing conditions can significantly affect the degradation behaviour of 4D-printed devices. Furthermore, the degradation rate may also be influenced by factors specific to the patient, such as the local biological environment, immune response, and individual healing rate. Researchers need to consider these variables when designing 4D-printed biomedical devices to ensure optimal performance and patient safety.

3.2. Fabrication Complexities.

3.2.1. Integration of Multiple Materials

One of the key advantages of 4D printing is the ability to create structures with varying mechanical properties and responsiveness to stimuli by incorporating different materials into the printed object. This capability is particularly important in biomedical applications, where devices often need to exhibit a range of properties, such as flexibility, rigidity, or responsiveness to specific stimuli, to function effectively. However, integrating multiple materials in a single 4D-printed structure can be challenging due to the limitations of current printing technologies. Achieving precise control over the distribution and interaction of different materials in a 4D-printed structure is essential to ensure the desired performance and behaviour of the final product. This requires advanced printing techniques that can deposit multiple materials simultaneously while maintaining precise control over their placement and interaction. Additionally, the materials used must be compatible with one another to prevent potential issues, such as delamination or poor adhesion between layers. Addressing these challenges will require the development of new printing techniques and material formulations specifically designed for multi-material 4D printing in biomedical applications.

3.2.2. Resolution and Accuracy

High resolution and accuracy are crucial in 4D printing for biomedical engineering, as the printed structures often need to have intricate features or precise dimensions to function effectively. For example, tissue engineering scaffolds require a high degree of porosity and precise pore geometry to promote cell attachment and growth [91], while implantable devices must have accurate dimensions to fit properly within the patient's body [39]. However, achieving the required resolution and accuracy in 4D printing can be challenging due to the limitations of current printing technologies.

3.2.3. Scalability

Scalability is another significant challenge in 4D printing for biomedical engineering, as the printed structures must often be produced in large quantities or at different scales to meet the needs of various patients. Moreover, the manufacturing process should be cost effective and time-efficient to ensure the widespread adoption of 4D-printed biomedical devices. However, many current 4D printing techniques are time-consuming and have limited scalability, making them unsuitable for large-scale production.

4. Future Directions for 4D Printing in Biomedical Engineering

As 4D printing technology continues to mature, there is immense potential for further advancements in biomedical engineering. This section highlights future directions for 4D printing in the field, offering novel solutions to pressing clinical challenges.

4.1. Emerging Trends and Areas of Research

4D printing involves the creation of smart materials that can change their properties or shape over time in response to external stimuli. As research and development in this field progress, several emerging trends and areas of research are expected to shape the future of 4D printing in biomedical engineering.

- Integration of Sensors and Electronics
- Biohybrid Systems
- Self-Healing Materials
- Personalised Medicine
- Environmental and Biodegradable Materials
- Multi-Stimuli Responsive Materials
- Biomimetic Materials
- Nanomedicine

4.2. Advancements in Fabrication Techniques

Advancements in fabrication techniques are crucial for driving innovation in 4D printing and other emerging technologies. As the field evolves, researchers continue to explore new methods and refine existing ones to create more sophisticated, efficient, and precise fabrication processes. Some notable advancements in fabrication techniques include.

4.2.1. Multi-Material and Multi-Process Printing

Multi-material and multi-process printing is a pivotal advancement in fabrication techniques, enabling the creation of complex, multifunctional structures by combining different materials and processes simultaneously. This innovation is particularly significant for 4D printing, where materials with diverse responsiveness to stimuli are often merged to achieve desired dynamic behaviours.

4.2.2. High-Resolution Printing

High-resolution printing has made significant strides in fabrication techniques, allowing for the creation of structures with intricate geometries and features at the micro- or even nano scale. This precision is crucial for applications such as tissue engineering and drug delivery systems, where fine control over structure and material properties is essential. Developments in high-resolution printing techniques, such as two-photon polymerization, have expanded the possibilities for fabricating complex 3D- and 4D-printed constructs, enabling a higher level of detail and functionality. This has led to the creation of more sophisticated medical devices, biomimetic tissues, and targeted drug delivery systems, among other applications. As research continues, further advancements in high resolution printing techniques will drive innovation in various fields, including biomedical engineering and nanotechnology, enhancing the potential impact and capabilities of 4D printing and other emerging technologies.

4.2.3. Hybrid Fabrication Techniques

Hybrid fabrication techniques, which combine multiple fabrication methods, have emerged as a key advancement in fabrication technology. These techniques unlock novel structures and functionalities by merging methods such as 3D printing with electro spinning or bioprinting with microfluidics. This synergy results in 4D-printed constructs with enhanced mechanical, biological, and stimuli-responsive properties. These hybrid techniques can create constructs with diverse characteristics, paving the way for new applications in biomedical engineering. For example, combining 3D printing with electrospinning can produce scaffolds with tunable mechanical properties and tailored pore structures, which are ideal for tissue engineering. Continued research into hybrid fabrication techniques will further expand the capabilities and potential applications of 4D printing, leading to novel innovations in various fields.

4.2.4. Self-Assembly and Self-Folding Techniques

Self-assembly and self-folding techniques are emerging as promising fabrication methods for creating complex 3D and 4D structures. By leveraging the inherent properties of materials and precise control of environmental conditions, these techniques enable the formation of dynamic constructs without the need for external manipulation or assembly. Self-assembly relies on the spontaneous organisation of materials into ordered structures, driven by molecular interactions and surface chemistry. Self-folding, on the other hand, involves inducing shape changes in materials through programmed stress patterns or stimuli-responsive elements [15,104,105]. Both approaches are vital for 4D printing applications, as they can produce structures that adapt and respond to environmental cues. for 4D printing in biomedical engineering, contributing to the development of innovative solutions and technologies.

4.2.5. Embedded Sensors and Actuators

Embedded sensors and actuators in 4D-printed constructs offer real-time monitoring and control of their behaviours, enabling the creation of smart structures that respond to various stimuli . Advances in fabrication techniques allow for the seamless integration of these components into printed constructs, enhancing their functionality. For instance, embedded sensors in tissue-engineered constructs can provide continuous monitoring of cellular activities. Further research in embedding sensors and actuators will unlock new possibilities in 4D printing, leading to innovative solutions across various domains of biomedical engineering.

4.2.6. Biofabrication

Biofabrication techniques, such as bioprinting and cell-laden hydrogel printing , have advanced significantly, enabling the incorporation of living cells and biomolecules within 3D- and 4D-printed constructs. This is essential for applications like tissue engineering and regenerative medicine, where interactions between printed materials and living cells are critical for success. Advancements in biofabrication have led to the creation of more biomimetic and functional tissue constructs, improving their integration within the body and promoting healing. As research progresses, biofabrication techniques will continue to evolve, allowing for more sophisticated 4D-printed constructs with enhanced biological properties, ultimately revolutionising healthcare and providing new therapeutic options.

4.2.7. Machine Learning and AI-Driven Design

Machine learning and AI-driven design have become increasingly important in the development and optimisation of fabrication processes, including 4D printing. These technologies can predict the behaviour of 4D-printed materials and structures, guiding the selection of materials, geometries, and fabrication parameters to achieve desired functionalities. Incorporating AI and machine learning into the design process allows for the exploration of vast design spaces, identification of optimal solutions, and prediction of material properties and performance. This leads to more efficient and effective fabrication processes and improved 4D-printed constructs. As research in AI and machine learning progresses, their integration into fabrication techniques will enhance the capabilities of 4D printing technology, enabling the creation of increasingly complex, functional, and responsive materials and structures across various applications and industries.

4.2.8. Stability and Automation

Scalability and automation are essential for translating 4D printing from research labs to real-world applications. Advancements in high-throughput manufacturing methods, automated quality control systems, and standardised processes and protocols will accelerate the large-scale production of 4D-printed constructs. By improving scalability and automation, 4D printing technology can become more accessible and cost-effective, paving the way for widespread adoption in biomedical engineering. As research continues, further innovations in scalable and automated fabrication techniques will play a crucial role in unlocking the full potential of 4D printing and driving its integration into various applications.

5. Conclusions

This review paper has provided a comprehensive overview of the advancements, challenges, and future directions for 4D printing in biomedical engineering. 4D printing technology has emerged as a promising approach to address various unmet clinical needs and revolution is healthcare practices by integrating the advantages of 3D printing with the added dimension of time-dependent shape transformations.

The paper has discussed the significant advancements in 4D printing for biomedical applications, including the development of stimuli-responsive materials, innovations in fabrication techniques, and successful implementation in various fields such as tissue engineering, drug delivery, and medical devices. Moreover, the review has highlighted several exciting future directions for 4D printing in biomedical engineering, such as the development of advanced smart materials, integration of bioprinting and 4D printing techniques, personalised medicine, nanomedicine, and bioelectronic devices. Addressing these challenges and exploring these future directions will be essential for realising the full potential of 4D printing technology in various biomedical applications.

As 4D printing technology continues to advance, it is poised to make significant contributions to biomedical engineering, ultimately improving patient outcomes and transforming healthcare practices. By fostering interdisciplinary collaboration, promoting public engagement and education, and encouraging industry partnerships, 4D printing has the potential to transform the way we approach the design and development of medical devices, treatments, and therapies. It is clear that 4D printing technology holds immense promise for the future of biomedical engineering, and continued research and innovation in this field will pave the way for innovative advancements in healthcare.

REFERENCES

[1] Asif, M.; Lee, J.H.; Lin-Yip, M.J.; Chiang, S.; Levaslot, A.; Giffney, T.; Ramezani, M.; Aw, K.C. A new photopolymer extrusion 5-axis 3D printer. Addit. Manuf. 2018, 23, 355–361. [CrossRef]

[2] Domett, P.; Arjmandi, M.; Ramezani, M. Design and manufacturing of knee implants for osteoarthritis patients. Solid State Phenom. 2020, 311, 1–11.

[3] Saeidi, M.; Gubaua, J.E.; Kelly, P.; Kazemi, M.; Besier, T.; Dicati, G.W.O.; Pereira, J.T.; Neitzert, T.; Ramezani, M. The influence of an extra-articular implant on bone remodelling of the knee joint. Biomech. Model. Mechanobiol. 2020, 19, 37–46. [CrossRef] [PubMed]

[4] Marinopoulos, T.; Li, S.; Silberschmidt, V.V. Structural integrity of 3D-printed prosthetic sockets: Experimental study for paediatric applications. J. Mater. Res. Technol. 2023, 24, 2734–2742. [CrossRef]

[5] Yang, J.; Yang, K.; Man, W.; Zheng, J.; Cao, Z.; Yang, C.-Y.; Kim, K.; Yang, S.; Hou, Z.; Wang, G.; et al. 3D bio-printed living nerve-like fibers refine the ecological niche for long-distance spinal cord injury regeneration. Bioact. Mater. 2023, 25, 160–175.[CrossRef]

[6] Abdullah, T.; Okay, O. 4D Printing of Body Temperature-Responsive Hydrogels Based on Poly(acrylic acid) with Shape-Memory and Self-Healing Abilities. ACS Appl. Bio Mater. 2023, 6, 703–711. [CrossRef]

[7] Patadiya, J.; Naebe, M.;Wang, X.; Joshi, G.; Kandasubramanian, B. Emerging 4D printing strategies for on-demand local actuation & micro printing of soft materials. Eur. Polym. J. 2023, 184, 111778.

[8] Asif, M.; Ramezani, M.; Khan, K.A.; Khan, M.A.; Aw, K.C. Experimental and numerical study of the effect of silica filler on the tensile strength of a 3D-printed particulate nanocomposite. Comptes Rendus Mec. 2019, 347, 615–625. [CrossRef]

[9] Li, M.; Assadian, M.; Ramezani, M.; Aw, K.C. Printed soft angular/torque sensors using carbon black-silicone composite. Sens. Rev. 2019, 39, 598–603. [CrossRef]

[10] Saeidi, M.; Ramezani, M.; Kelly, P.; Neitzert, T.; Kumar, P. Preliminary study on a novel minimally invasive extra-articular implant for unicompartmental knee osteoarthritis. Med. Eng. Phys. 2019, 67, 96–101. [CrossRef]

[11] Pasang, T.; Ramezani, M.; Prygoski, M.;Wanhill, R.; Byrnes, R.; Kamiya, O.; Tanaka, K. Fatigue of commercially pure titaniumdental implants. Mater. Phys. Mech. 2016, 27, 79–89.

[12] Arjmandi, M.; Ramezani, M.; Bolle, T.; Köppe, G.; Gries, T.; Neitzert, T. Mechanical and tribological properties of a novel hydrogel composite reinforced by three-dimensional woven textiles as a functional synthetic cartilage. Compos. Part A Appl. Sci. Manuf. 2018, 115, 123–133. [CrossRef]

[13] Taneja, H.; Salodkar, S.M.; Singh Parmar, A.; Chaudhary, S. Hydrogel based 3D printing: Bio ink for tissue engineering. J. Mol. Liq. 2022, 367, 120390. [CrossRef]

[14] Muhindo, D.; Elkanayati, R.; Srinivasan, P.; Repka, M.A.; Ashour, E.A. Recent Advances in the Applications of Additive Manufacturing (3D Printing) in Drug Delivery: A Comprehensive Review. AAPS PharmSciTech 2023, 24, 57. [CrossRef] [PubMed]

[15] Zhang, Y.; Raza, A.; Xue, Y.-Q.; Yang, G.; Hayat, U.; Yu, J.; Liu, C.; Wang, H.-J.; Wang, J.-Y. Water-responsive 4D printing based on self-assembly of hydrophobic protein “Zein” for the control of degradation rate and drug release. Bioact. Mater. 2023, 23, 343–352. [CrossRef]