REVIEW ARTICLE

4D Printing: An Innovative Technology For Self-transforming Structures and Multidisciplinary Applications

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Abstract

4D printing, an innovative technology merging conventional additive manufacturing with smart materials and external stimuli, empowers objects to undergo transformative processes over time, exhibiting qualities like self-sensitivity, self-assembly, and self-healing. This technology harbors the potential to reshape modern construction practices, aligning with the demand for autonomous, energy-efficient, and environmentally sustainable structures. Furthermore, 4D printing proves valuable in medicine and aerospace. 4D printing can revolutionize aerospace manufacturing and design by enabling the creation of smart, adaptive, and highly efficient components and structures that can enhance the performance, reliability, and sustainability of aerospace systems. In the domain of conventional robotics, rigid materials such as metals, hard plastics, and ceramics are predominantly employed in the construction of robotics that can efficiently respond to a multitude of stimuli. Textiles offer self-sustainability, reduced material consumption, and enhanced adaptability. Despite challenges, 4D printing holds significant potential across various domains, urging substantial research and development efforts for its successful integration.

Key words: 4D printing, applications, materials, methods

INTRODUCTION

4D printing is a substantial breakthrough above regular additive manufacturing (AM) in that it incorporates the temporal dimension into inert constructions as shown in Figure 1. It is based on smart materials and their capacity to respond to environmental stimuli including temperature, light, and electrical forces.

Figure 2 mentions the fourth dimension in 4D printing, which emphasizes the temporal evolution of the produced components. Skylar Tibbits, a researcher at the Massachusetts Institute of Technology, first unveiled this breakthrough concept of self-assembly and programmable materials in 2012. Over the last decade, 4D printing has seen an exponential increase in study papers, piquing the interest of interdisciplinary scholars and engineers.[1] The bulk of 4D printing structures are built utilizing techniques like fused deposition modeling and stereolithography. However, the procedure employed is dictated by the specific material used and the complexity of the intended shape. The revolutionary potential of 4D printing, which allows autonomous structural evolution over time without incurring additional time, money, or components, has produced various potential uses.[2]

This comprehensive review highlights the significant strides made in the realm of 4D printing within the domain of biomedical applications. Despite the rapid evolution of this technology, researchers are confronted with specific constraints when endeavoring to fabricate soft robotics, dynamically engineered tissues, and patient-specific

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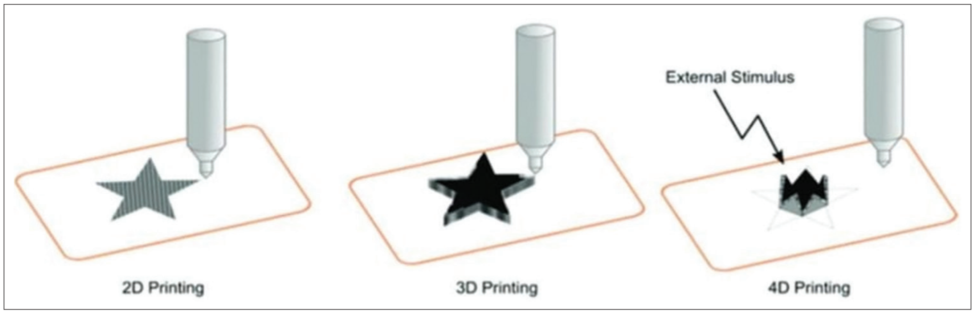

Figure 1: Images of 2D, 3D, and 4D printing

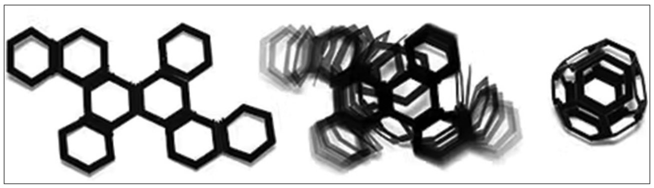

Figure 2: Dimension examples

controlled drug delivery implants, all of which harbor substantial promise for minimally invasive surgical procedures. These constraints can be delineated into two overarching categories: Those associated with design and those rooted in the manufacturing process. Design-related challenges encapsulate a dearth of comprehensive insights into the intricacies and feedback mechanisms of biological systems. These challenges encompass issues about the response time of three-dimensional constructs and the precise controllability of shape memory materials (SMMs).

Conversely, manufacturing-based limitations revolve around the accessibility of appropriate 3D printing technologies and biocompatible smart materials deemed suitable for the domain of 4D printing. For instance, extrusion-based techniques are hampered by diminished printing speed and constrained resolution capabilities.[3] Meanwhile, light-assisted techniques, while holding promise, are often encumbered by their elevated cost and frequently lack the capacity for multi-material printing. Furthermore, the concept of material permeability assumes critical significance across various applications, notably in the realms of biomedical engineering and drug delivery. Shape memory polymers (SMPs) exhibit limitations in terms of permeability, whereas hydrogels present a more favorable and permeable nature.[4] This disparity introduces challenges when contemplating the complete substitution of hydrophilic gel materials with SMP.

MATERIALS USED IN 4D PRINTING

Recent advancements in 3D printing have made it possible to arrange materials more precisely and flexibly, which has greatly aided 4D printing. Since the materials used in 4D printing can modify their properties over time, they are frequently referred to as smart materials. These materials exhibit activities like self-assembly, self-healing, form memory, and self-capability and can react to external stimuli. In addition to using materials that may change shape, 4D printing also uses materials that can change color when exposed to ultraviolet and visible light.[5] Based on how they react to stimuli, the many types of smart materials utilized in 4D printing will be covered in the sections shown in Figure 3.

Materials responsive toward moisture: Hydrogels

Materials that are sensitive to moisture or water have garnered a lot of interest due to their wide range of potential applications as mentioned in Figure 4. Due to their extraordinary ability to respond to moisture or water, these compounds are also known as hydrogels. They truly belong to a class of crosslinked polymer chain 3D networks that, when exposed to moisture, can expand by up to 200% of their initial volume. Hydrogels are also excellent candidates for 3D printing since they can be folded, bent, stretched, and expanded geometrically. They are highly biocompatible and straightforward to print when used with direct ink writing.[6-8] The main drawback is that, due to their sluggish reverse reaction, they take hours to dry and shrink.

Materials responsive toward temperature: Thermo-responsive

These are the intelligent materials that react to stimuli involving heat or temperature. Two mechanisms – the shape change effect or the shape memory effect (SME) – are primarily responsible for these materials' changes in shape in response to thermal stimuli. SME is the use of external stimuli to restore the original shape of a distorted (plastic) material.[9] SMMs, which are smart materials that exhibit the SME effect, include shape-memory gels (SMGs), shape memory alloys (SMAs), shape-memory ceramics (SMCs), and shape-memory hybrids (SMHs).

SMMs are further divided into one-way, two-way, and three-way materials depending on the number of shape transformations. In one-way SMMs, the initial shape cannot be regained after deformation whereas in two and three-way SMMs the original shape can be regained after deforming into a temporary shape via an intermediate shape.[10]

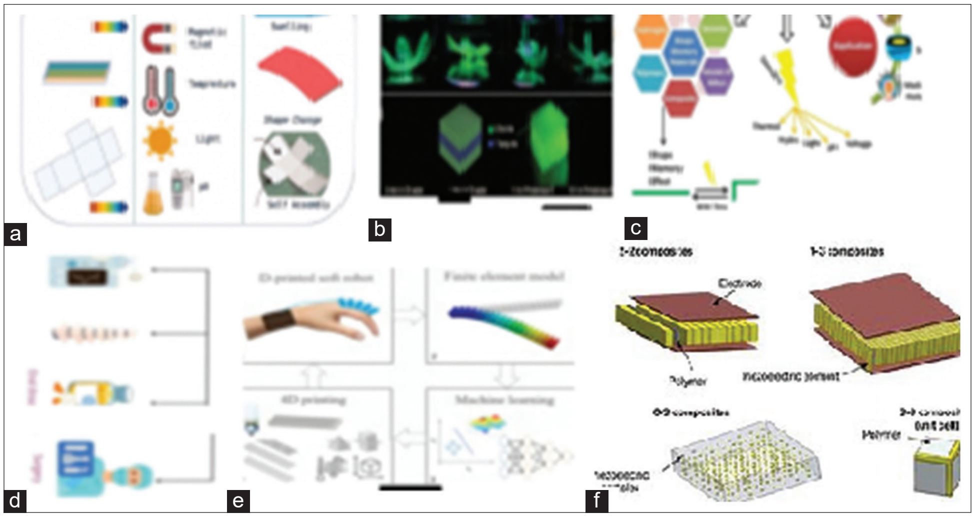

Figure 3: Materials responsive toward (a) moisture: Hydrogels (b) temperature: Thermo-responsive (c) the light: photo-responsive (d) the electric energy: electro-responsive (e) the magnetic energy: Magneto-responsive (f) piezoelectric materials

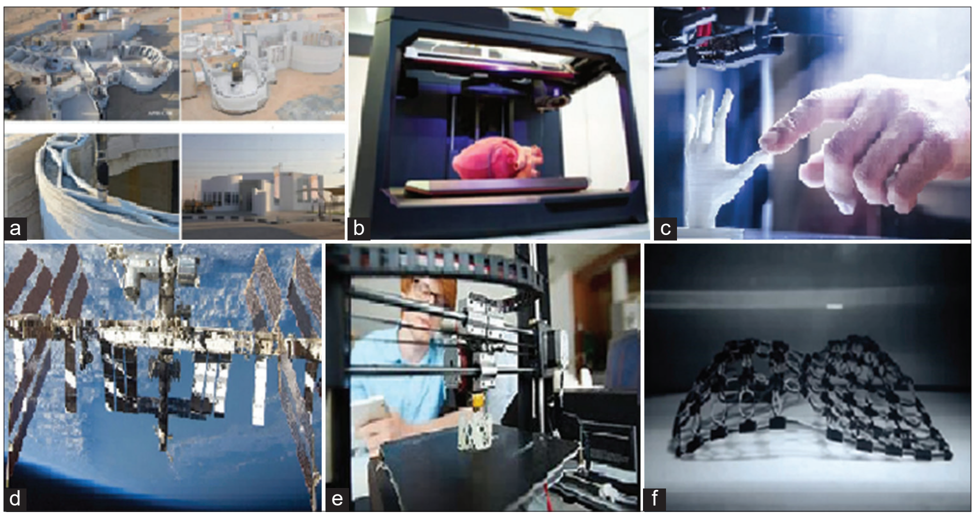

Figure 4: 4D printing applications in (a) construction (b) medicine (c) robotics (d) aerospace (e) electronics (f) textiles

Materials responsive toward the light: Photo-responsive

In addition, light serves as a subliminal cue for the deformation of intelligent materials. When a portion of a smart material – also known as a photo-responsive material – is exposed to light, the area absorbs the light, which eventually causes the heating phenomenon in the material. As heat works as a stimulant for the deformation of smart materials, causing the photo-responsive material to alter its shape. Because light does not bring about a change directly like heat and moisture do, it functions as an indirect stimulus. Liu *et al*. demonstrated a sequential self-folding construction where the light is absorbed by the joints and they heat up causing the form change.[11]

The type of lighting used and the color of the joints both affect how quickly heat is absorbed by the joints. Kuksenok *et al*. employed light in a different method in a different study to cause deformation in the photo-responsive material. They injected a chromophore – a photosensitive substance – into a few chosen regions of a polymer block (gel), causing just those regions to deform when light is shone on the structure.

Materials responsive toward the electric energy: Electro-responsive

Electricity is a similar indirect stimulation to light in that it has been demonstrated to have a heating impact on the materials it passes through. So-called electro-responsive materials are those that deform due to their responsive behavior to the electric current. A silicon elastomer and ethanol mixture were used by Miriyev *et al*. to create an artificial muscle. When current is applied to a muscle, the ethanol evaporates, increasing the volume of the muscle and ultimately causing deformation or expansion of the muscle electricity can influence the absorption or desorption of water in polypyrrole

(PPy), and Okuzaki *et al*. used this idea to create microrobots (origami) out of PPy.[12] When the robot was kept in humid conditions, due to the absorption of moisture, a voltage was developed which drives its head forward.

Materials responsive toward magnetic energy: Magneto-responsive

Another indirect stimulus that might cause deformation in smart materials is the magnetic field or the magnetic energy. In addition, materials that deform in response to magnetic energy are referred to as magneto-responsive materials since they are utilized to print 4D structures. Breger *et al*. used magnetic nanoparticles in a microgripper (printed from hydrogel) to accomplish a remote-control mode. The printed structure started to exhibit responsiveness that can be controlled by a remote when a magnetic field was applied to it.[13,14] There is tremendous potential for 4D printed structures made of magneto-responsive materials in the field of printing metal and polymers, but there is one drawback: The print size needs to be small and light to avoid being impacted by magnetic fields.

Piezoelectric materials

When subjected to mechanical stress, piezoelectric materials can generate a charge. Piezoelectricity is the process of creating electric charges as a result of a mechanical force. Piezoelectric materials are also suitable for 4D printing since they may distort when subjected to mechanical forces. The phenomenon is straightforward: When stress is applied, charges are generated, and these charges eventually cause the structure to alter[15] (because charges can result in deformation).

Materials responsive to pH

These are intelligent materials that can adapt to pH levels and change their shape and volume accordingly. They are suitable for 4D printing technology due to the shape distortion in response to varying pH values. Since polyelectrolytes feature an ionizable side group, they can accept or give protons when the pH value changes, making them pH-responsive polymers that have been employed in 4D printing.[16-18] Electrostatic repulsion causes the polymer chain to stretch when a proton is released, deforming the structure. When a proton is accepted, the structure returns to its original shape.

Polyelectrolytes have polyanions or poly acids (carboxyl or sulphonic groups) as the ionizable side chains and polycations or poly-bases (such as ammonium salt) as the functional group.[19] At higher pH levels, the side chains release the proton (stretch), while at lower pH levels, they take the proton (neutralize).

APPLICATIONS IN 4D PRINTING

4D printing is emerging as a promising technology for various applications in construction, medicine, robotics, the aerospace sector, electronics, and textiles as shown in Figure 4.

CONSTRUCTION

The discernible allure of 4D printing lies in its potential to revolutionize modern construction practices, aligning with the growing imperative for autonomous, energy-efficient, and environmentally sustainable structures.[20] However, on conducting a meticulous scientific assessment of 4D printing's application within the domains of civil construction and architecture, it becomes evident that this technology remains in its embryonic stage, predominantly confined to laboratory-scale experiments.[21-23] This concerted work is indispensable for the eventual integration of 4D printing into mainstream applications within the realms of civil construction and architecture, facilitating the realization of its full potential.[24]

MEDICINE

4D printing opens new horizons in diagnostic tools. The technology enables the development of adaptive and responsive devices, such as diagnostic sensors, that can interact with the human body in unique ways.[25] These sensors have the potential to enhance the monitoring of physiological parameters, detect specific biomarkers, and offer early disease diagnosis, thereby significantly impacting the healthcare industry.[26] In the domain of medical implants, 4D printing introduces groundbreaking possibilities.[27] The ability to create implants with adaptive and self-transforming features is particularly promising. These smart implants could dynamically respond to changing physiological conditions within the body, optimizing their functionality and longevity. Furthermore, the customization of medical implants for individual patients becomes more feasible with 4D printing, potentially reducing complications and improving patient outcomes. The application of 4D printing extends to drug delivery systems as well. By engineering drug-releasing structures that respond to specific stimuli, it becomes possible to develop highly targeted and precise therapeutic approaches.[28]

ROBOTICS

Central to the advancement of soft robotics is the application of soft and intelligent materials, most notably electroactive polymers (EAPs), which facilitate gentle interactions with delicate objects. This unique attribute renders soft robots significantly more resilient against potentially destructive external forces, setting them apart from traditional robotic systems.[29-31] Within the context of soft robotics, 4D printing structures present an appealing prospect. These structures are distinguished by their inherent flexibility, deformability, and responsiveness to environmental fluctuations. 4D printing enables the efficient production of actuators designed for soft robots.[32] For example, a breakthrough by Rossiter *et al*. involves the utilization of 3D printing techniques to fabricate dielectric elastomer actuators (DEAs), effectively mitigating the challenges related to time-intensive and laborious traditional DEA production methods. DEAs are categorized as EAP smart materials, capable of responding to electrical stimuli. When an electrical charge is applied to a DEA, it transduces this energy into mechanical motion, inducing deformation and generating motion within the robotic system.[33]

AEROSPACE

4D printing is emerging as a promising technology for various applications in the aerospace sector.[34] An intriguing example is the International Space Station, which has already experimented with 3D printing of acrylonitrile butadiene styrene (ABS) structures in microgravity conditions. Moreover, 4D printing offers the advantage of reduced printing times, enabling on-site production of components within spacecraft. This capability reduces the reliance on Earth for sourcing critical components, enhancing the autonomy of space missions.[35] A vital feature in space missions is the utilization of self-sustainable materials. 4D printed structures possess the unique ability to self-assemble based on prevailing conditions, which can be a transformative asset in such missions.

ELECTRONICS

4D printed structures detect changes in external variables with exceptional sensitivity and precision, including moisture levels, temperature fluctuations, stress and strain, differences in electric and magnetic fields, and pH shifts.[36] Shape memory alloys (SMAs), typically used as actuators, provide a new dimension by acting as sensors for sensing temperature fluctuations, strain levels, and structural fatigue. Ultrasonic additive manufacturing (UAM), a technology that mixes metals and smart materials to create intelligent structures, has the potential to transform the manufacturing of smart vehicles and airplanes. UAM, a subset of 3D printing, allows for the fabrication of intelligent materials, including 4D structures.[14]

TEXTILES

In the textile industry, 4D printing introduces exciting opportunities for textiles to dynamically adapt to changing environmental conditions.[37] This adaptability optimizes comfort and ventilation, ensuring that textiles remain functional and esthetically pleasing under varying circumstances. 4D printed textiles can adjust not only in terms of shape but also in color and texture, enhancing their utility and esthetics.[38] These adaptable textiles can be printed on a variety of materials, including cotton, polypropylene, polywood, and polyester, using materials such as PLA, ABS, and Nylon.[39] In addition, the film and fashion industry has begun to explore 3D-printed outfits, gaining attention for their innovative designs and the potential for personalized and highly creative apparel.

CONCLUSION

4D printing, a remarkable fusion of additive manufacturing, smart materials, and external stimuli, ushers in a new era of possibilities across various domains. This innovative technology enables objects to exhibit self-sensitivity, self-assembly, and self-healing over time, promising transformative applications. While 4D printing holds immense potential for revolutionizing construction practices, it is in its nascent stage, primarily limited to laboratory experiments. Overcoming challenges related to the fabrication of large components and mastering transformations and stimuli is essential to integrating 4D printing into mainstream construction and architecture. 4D printing is at the forefront of medical innovation, offering the creation of highly detailed medical models, adaptive diagnostic tools, advanced medical implants, and precise drug delivery systems. It seamlessly integrates with other disciplines, paving the way for personalized medicine and significantly impacting healthcare. The application of 4D printing to soft robotics presents a path toward more flexible and adaptable robots. Research is ongoing to optimize the production of actuators and facilitate autonomous self-assembly, promising advancements in the field. 4D printing offers cost-effective, adaptive, and self-sustaining solutions for space missions. Components can be manufactured on-site, reducing reliance on Earth for sourcing materials and enhancing the autonomy of space exploration. 4D printing advances the development of advanced sensors and materials that are lightweight, sensitive, and responsive to various stimuli. The potential for sensor applications in vehicles and aircraft is particularly promising. 4D printing technology offers the prospect of creating self-healing structures and rectifying errors and defects in construction, thereby promoting sustainability and reducing material consumption. 4D printing introduces exciting opportunities for textiles to dynamically adapt to changing environmental conditions, offering enhanced comfort, ventilation, and esthetics. 4D printing is a groundbreaking technology that, although facing challenges, offers transformative potential across diverse domains. Substantial research and development efforts are needed to unlock its full capabilities and successfully integrate it into mainstream applications. This multidisciplinary approach has the power to reshape industries and improve the sustainability and adaptability of various products and systems.

REFERENCES

1. Bharani Kumar S, Jeevamalar J, Ramu P, Suresh G, Senthilnathan K. Evaluation in 4D printing A review. Mater Today Proc 2021;45:1433-7.
2. Calvert P. Hydrogels for soft machines. Adv Mater 2009;21:743-56.
3. Shinde S, Mane R, Vardikar A, Dhumal A, Rajput A. 4D printing: From emergence to innovation over 3D printing. Eur Polym J 2023;197:112356.
4. Mitchell A, Lafont U, Hołyńska M, Semprimoschnig C. Additive manufacturing-A review of 4D printing and future applications. Addit Manuf 2018;24:606-26.
5. Wu J, Yuan C, Ding Z, Isakov M, Mao Y, Wang T, *et al*. Multi-shape active composites by 3D printing of digital shape memory polymers. Sci Rep 2016;6:24224.
6. Xu X, Lin X, Yang M, Chen J, Huang W. Microstructure evolution in laser solid forming of Ti-50 wt% Ni alloy. J Alloys Compd 2009;480:782-7.
7. Shie MY, Shen YF, Astuti SD, Lee AK, Lin SH, Dwijaksara NL, *et al*. Review of polymeric materials in 4D printing biomedical applications. Polymers (Basel) 2019;11:1864.
8. Gomes KC, Carvalho M, de Paula Diniz D, Abrantes RC, Branco MA, de Carvalho Junior PR. Carbon emissions associated with two types of foundations: CP-II Portland cement-based composite vs. geopolymer concrete. Matéria (Rio de Janeiro) 2019;24:1-10.
9. Frigione M, de Aguia JL. Innovative materials for construction. Materials (Basel) 2020;13:5448.
10. Zhang P, Han S, Golewski GL, Wang X. Nanoparticle-reinforced building materials with applications in civil engineering. Sage J 2020;12:1-4.
11. Guilaine J. A personal view of the neolithisation of the Western Mediterranean. Quat Int 2018;470:211-25.
12. Okuzaki H, Hosaka K, Suzuki H, Ito T. Humido-sensitive conducting polymer films and applications to linear actuators. React Funct Polym 2013;73:986-92.
13. Ofori-Kuragu JK, Osei-Kyei R. Mainstreaming Pre-manufactured Offsite Processes in Construction Are We Nearly There? In: Proceedings of the Institution of Civil Engineers Structures and Buildings; 2021. p. 1-19.
14. Niendorf T, Brenne F, Krooß P, Vollmer M, Günther J, Schwarze D, *et al*. Microstructural evolution and functional properties of Fe-Mn-AI-Ni shape memory alloy processed by selective laser melting. Metall Mater Trans A 2016;47:2569-73.
15. Bodaghi M, Damanpack AR, Liao WH. Adaptive metamaterials by functionally graded 4D printing. Mater Des 2017;135:26-36.
16. Leng J, Lan X, LiuY, Du S. Shape-memory polymers and their composites: Stimulus methods and applications. Prog Mater Sci 2011;56:1077-135.
17. Yan C, Hao L, Xu L, Shi Y. Preparation characterisation and processing of carbon fiber/polyamide-12 composites for selective laser sintering. Compos Sci Technol 2011;71:1834-41.
18. Hoa SV. Development of composite springs using 4D printing method. Compos Struct 2019;210:869-76.
19. Wang D, Zhang W, Han B. New generation of cement-based composites for civil engineering. In: New Materials in Civil Engineering. Ch. 25. Netherlands: Elsevier Science; 2020. p. 777-95.
20. Atwell BJ, Kriedemann PE, Heuvelink E. Plants in action: Adaptation in nature, performance in cultivation: C.G.N. Turnbull (Eds.); MacMillan Education Australia, South Yarra, Victoria, Australia. *Ann Bot* 1999;84:170-3.
21. Jain K, Vedarajan R, Watanabe M, Ishikiriyama M, Matsumi N. Tunable LCST behavior of poly(*N*-isopropylacrylamide/ionic liquid) copolymers. Polym Chem 2015;6:6819-25.
22. Chan BQ, Chong YT, Wang S, Lee CJ, Owh C, WangF, *et al*. Synergistic combination of 4D printing and electroless metallic plating for the fabrication of a highly conductive electrical device. Chem Eng J 2022;430:132513.
23. Navaf M, Sunooj KV, Aaliya B, Akhila PP, Sudheesh C, Mir SA, George J. 4D printing: A new approach for food printing; Effect of various stimuli on 4D printed food properties. A comprehensive review. Appl Food Res 2022;2:100150.
24. Ge Q, Sakhaei AH, Lee H, Dunn CK, Fang NX, Dunn ML. Multimaterial 4D printing with tailorable shape memory polymers. Sci Rep 2016;6:31110.
25. Mao Y, Ding Z, Yuan C, Ai S, Isakov M, Wu J, *et al*. 3D printed reversible shape changing components with stimuli responsive materials. Sci Rep 2016;6:24761.
26. Lopez-Valdeolivas M, Liu D, Broer DJ, Sanchez-Somolinos C. 4D printed actuators with soft-robotic functions. Macromol Rapid Commun 2018;39:1-7.
27. Mao Y, Yu K, Isakov MS, Wu J, Dunn ML, Jerry Qi H. Sequential self-folding structures by 3D printed digital shape memory polymers. Sci Rep 2015;5:13616.
28. Ryu J, D'Amato M, Cui X, Long KN, Jerry Qi H, Dunn ML. Photo-origami bending and folding polymers with light. Appl Phys Lett 2012;100:161908.
29. Miao S, Zhu W, Castro NJ, Nowicki M, Zhou X, Cui H, *et al*. 4D printing smart biomedical scaffolds with novel soybean oil epoxidized acrylate. Sci Rep 2016;6:27226.
30. Ge Q, Dunn CK, Jerry Qi H, Dunn ML. Active origami by 4D printing. Smart Mater Struct 2014;23:1-15.
31. Cataldi P, Liu M, Bissett M, Kinloch IA. A review on printing of responsive smart and 4D structures using 2D materials. Adv Mater Technol 2022;7:2200025.
32. Pei E, Loh GH. Technological considerations for 4D printing: An overview. Prog Addit Manuf 2018;3:95-107.
33. Wonjin J, Jang HI, Harianto RA, So JH, Lee H, Lee HJ, *et al*. Introduction of 3D printing technology in the classroom for visually impaired students. J Vis Impair Blind 2016;110:115-21.

34. Kang HW, Lee SJ, Ko IK, Kengla C, Yoo JJ, Atala A. A 3D bioprinting system to produce human-scale tissue constructs with structural integrity. Nat Biotechnol 2016;34:312-9.
35. Lopes PA, Paisana H, De Almeida AT, Majidi C, Tavakoli M. Hydroprinted electronics: Ultrathin stretchable Ag-In-Ga E-skin for bioelectronics and human-machine interaction. ACS Appl Mater Interfaces 2018;10:38760-8.
36. Koch HC, Schmelzeisen D, Gries T. 4D textiles made by additive manufacturing on pre-stressed textiles an overview. Actuators 2021;10:31.
37. Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Cham: Springer; 2014. p 1-495.
38. Mu T, Liu L, Lan X, Liu Y, Leng J. Shape memory polymers for composites. Compos Sci Technol 2018;160:169-98.
39. Ding Z, Yuan C, Peng X, Wang T, Qi HJ, Dunn ML. Direct 4D printing via active composite materials. Sci Adv 2017;3:e1602890.

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