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Significant advancements of 4D printing in the field of orthopaedics

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ABSTRACT

Researchers, engineers and doctors are continuously focusing on the development of orthopaedics parts characterised by the required responses. So, advanced manufacturing technologies are introduced to fulfil various previously faced challenges. 4D printing provides rapid development with its capability of customization of smart orthopaedics implants and appropriate surgical procedure. This technology opens up the making of innovative, adaptable internal splints, stents, replacement of tissues and organs. Thus, to write this review based article, relevant papers on 4D printing in medical/orthopaedics and smart materials are identified and studied. 4D printed parts show the capability of shape-changing and self-assembly to perform the required functions, which otherwise manufactured parts are not providing. Smart orthopaedics implants are used for spinal deformities, fracture fixation, joint, knee replacement and other related orthopaedics applications. This paper briefs about the 4D printing technology with its major benefits for orthopaedics applications. Today various smart materials are available, which could be used as raw material in 4D printing, and we have discussed capabilities of some of them. Due to the ability of shape-changing, smart implants can change their shape after being implanted in the patient body. Finally, twelve significant advancements of 4D printing in the field of orthopaedics are identified and briefly provided. Thus, 4D printing help to provide a significant effect on personalised treatments.

1. Introduction

4D printing technologies use the same set of technologies as being used in 3D printing. However, the main difference is the use of smart material which is printed, layer by layer from the input of Computer-Aided Design (CAD) digital model. This technology adds one more dimension of the time by which printed part can change their shape with respect to time and other environmental parameters like temperature, pressure, humidity etc. Materials used are programmable which respond to the specific environment with the required design. The part printed by this technology is transforming itself into another structure with external energy. The applications of 4D printing are introduced in orthopaedics to manufacture customised smart implants and other required tools and devices.[1,2]

Shape, size and few materials properties of a part can now be controlled through the available 4D printing technologies. It can print components in both a macro and micro scale. 4D printing allows fabricating of dynamically reconfigurable structure using suitable materials and cells. It can use a variety of smart material, having transforming configuration. In the medical field, this technology is useful to create self-reconfigurable protein, tissue and organs. The growth of this technology is continuously increasing in the healthcare market. This enables to create complex shape parts with intricate details and features. It provides a significant transformation in the medical field.[3,4]

4D printed objects have 'fold' or 'unfold' capability in predetermined shapes. Smart self cylindrical pipe manufactured by these materials are useful for the proper flow of fluid. These can control the flow of fluid as per our requirement. 4D printing has great potential in the construction areas, which can be extreme as per climate change.[5,6] It increases the construction efficiency using programmable materials. It has various applications in aerospace such as engine cooling, self-deploying air ventilation structure and other uses.

4D printed pieces of equipment can be used successfully for healthcare, defence, aerospace and automotive industries. This technology is used to increase the efficiency of the products. It has the capability of self-repairing and self-assembling. In defence, it is used for making military uniforms which are used to protect

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against poisonous gases. It can also be utilised to print car seat, which can provide adaptive support and comfort.[7,8] This technology is used for future medical and engineering applications.

2. 4D printing

4D printing uses additive manufacturing technique by which part is manufacture layer by layer from the input of CAD data using smart material. It provides innovative possibilities for the manufacturing of 3D parts incorporating the fourth dimension of time. These parts can reshape themselves by reacting to the changing of conditions. This technology provides a disruptive effect in orthopaedics due to its customised capability with respect to time.[9,10] By the applications of this technology, some dreams are fulfilled which are not fulfilled by the 3D printing technology.

4D printing uses programmable materials having responsive self-assembly, which show the ability to change their properties and functions according to the requirements. This technology is also used in tissue engineering applications to fabricate the complex and sensitive structure. It has superior technique in terms of efficiency, performance and quality to manufacture a new product. This technology provides a highly viable, useful, responsive and useful system in orthopaedics for the production of smart bone implants, tools and important instruments. It generates meta-material structures which changes the operational environment. Printed parts have the capability like twisting, elongating, bending and corrugating. These have sequential folding and deforming capability.[11]

3. Need for 4D printing in orthopaedics

Researchers and technologists are continuously focusing on the potential applications of 4D printing. This technology creates endless possibilities in the field of orthopaedics. 4D printed orthopaedics implants can grow as human exposed the growth that's the main reason to introduce this technology in the field of orthopaedics.[12,13] These parts rapidly react with temperature changes or atmospheric pressure and also can change their structure and look with light and pressure. As compared to 3D printing, 4D printing could make major disrupt in the various industries. It gives a new understanding of the applications, research and development of the orthopaedics products. These provide positive growth in the industry with minimum risk.[14,15] This paper discusses 4D printing and its significant benefits and then takes up various smart materials which could be used in 4D printing technology.

4. Benefits of 4D printing

4D printing is a next-generation technique used to manufacture complex and flexible parts with high precision. By the applications of intelligent materials, it has the potential to manufacture patient-specific scaffolds for tissue generation.[16–18] This technology is used to print polymeric abiotic material with living cells. 4D Printed parts show smart behaviour. Thus the major benefits of these parts are below:

- Spatial and temporal control during the manufacturing of the product
- Produce dynamic structure
- On-demand dynamically shapes can be made
- Can manufacture a flexible part
- Printed part meets the performance standard
- Excellent physical and functional properties in a controlled manner
- Improved manufacturing efficiency with 4D printing
- The printed product changes their shape, colour and function
- Minimum post-processing requirement
- Reduced manufacturing cost for a single piece customised part

4D printing provides unique interactions to print attractive orthopaedics parts as per the requirements of a patient. This technology is useful to manufacture on-demand desired shape with the integration of time. It has good potential to develop nano smart biomedical devices like actuator, biosensors which can easily monitor various changes in orthopaedics. This is capable of using smart, robust material which can precisely create the part. Orthopaedics implants manufactured by this technology are soft and flexible, having lesser pain after interaction into the patient body.[19,20]

5. Different smart materials can be used in 4D printing

The unique materials used in this technology have the fourth dimension of time. Its applications are in medical, manufacturing aerospace and other important areas. Products adopt a new shape which can improve quality and safety in healthcare. Table 1 provides different smart materials that can be used for 4D printings applications.

4D printing can be use different types of smart materials. These materials are flexible, precise and useful for self-construction structure. Each type of material has its capability and application to perform the required functions. Shape memory polymers show the capability to return from its temporary state to the original state with external stimulus like change in temperature. This technology can also print the data captured by using 3D scanner.[39]

6. Major advancements of 4D printing in orthopaedics

4D printed parts have precise properties to achieve success in the orthopaedics field. Smart biomaterial printed by this technology behaves somewhat like natural after implanting in the patient body. It provides functionality and creative medical devices to improve patient outcomes. It enhances the performance and the functionality of orthopaedics implants. These implants are easy to use and have excellent durability and flexibility.[40,41] Table 2 discusses the significant advancements of 4D printing in orthopaedics.

4D printed implants seem to have reduced risk after they are implanted into the patient body. These parts can be monitored to specific changes to improve patient comfort. This technology effectively creates dynamically shapes spinal implants to provide strength to the spine. It creates freedom of design during the production of a complex structure. It plays a vital role in the field of bone tissue engineering and other orthopaedics surgery.[63,64] Biomedical splint manufactured by this technology can rapidly adapt the changes with the change in temperature. It provides flexible and innovative solution of the children by creating smart implants.

7. Major contributions of the study

4D printing technology is capable of making a product smarter and more functional. Its applications are in regenerative medicine to repair the living organisms. Researchers are continuously working to overcome the potential issue related to 4D printing. Stents manufactured by this technology responds to magnetic fields which can control its shape and size as per the required functions. 4D printed splints have great potential to change their shape as per individual patients need. Its applications are also for the manufacturing of scaffolds and nano tissue. It includes stimuli response effects to provide a dynamic change in tissue

Table 1
Different smart materials that can be used in 4D printing.

S No	Smart material	Description	References
1	Shape memory alloys	• This material gets deformed when cooled and gets to its pre-deformed shape when heated • It is lightweight which is used efficiently to manufacture hermetic joints in metal tubing • Most common shape memory alloys are nickel-titanium and copper-aluminium alloys	Li et al., 2016[21]; Yuan et al., 2018[22]
2	Electroactive polymers	• This polymer changes their shape and size when stimulated by an electric field • It is used for sensor and actuators • Used for the development of artificial muscle and microfluidic devices	Ning et al., 2018[23]; Palza et al., 2019[24]
3	Shape memory polymers	• Shape memory polymers are used in 4D printing due to its low cost, low density, ease of use and its chemical modification ability • It has great potential to return to its original shape from the deforming stage with the change in temperature • The shape of the material can be changed by triggering off the magnetic or electric field	Díaz Lantada, 2017[25]; Govindarajan and Shandas, 2017[26]
4	Magnetic shape memory alloys	• These materials produce deformation and force with the response of magnetic field • These alloys include Manganese, Nickel and Gallium • These materials operate between −40 and 60 °C and can change its electric resistivity and magnetic permeability during deformation	Haldar and Lagoudas, 2014[27]; Bruno et al., 2017[28]
5	Smart inorganic polymers	• These materials are fully inorganic polymers having stimuli-responsive like rheology, conductivity, bioactivity, sensing etc • These materials have smart properties and useful for biosensing applications • Have diverse applications for tissue regeneration, tissue repair and drug delivery	Yan et al., 2016[29]; Tomczykowa et al., 2019[30]
6	Electro-responsive polymers	• This polymer can change its volume and shape with the response to various electrical stimuli • Materials are useful to convert the electrical energy into mechanical work • These materials are used to manufacture soft artificial muscle using 4D printing technology	Rahimi et al., 2014[31]; Verbrugghe et al., 2015[32]
7	Temperature responsive polymers	• These polymers show a discontinuous change in their physical properties concerning temperature • These are stimuli-responsive materials which can change their properties with environmental conditions • Major applications are drug delivery, liquid chromatography and bioseparation	Karimi et al., 2016[33]; Nagase et al., 2019[34]
8	Photoresponsive polymer	• It undergoes the physical and chemical transformation which induces changes like polarity, conformation, hydrophilicity and optical properties • It is unique stimuli-responsive materials which can change its properties using light irradiation • Show good processability during printing and suitable for the biomedical research	Marturano et al., 2016[35]; Yang et al., 2017[36]
9	Smart hydrogels	• These are stimuli-responsive hydrogel having the ability of external and internal stimuli changes • This hydrogel material changes the shape with exposure to temperature changes • 4D printing uses smart hydrogel to create the living structure of human tissue and organs	Du et al., 2015[37]; Ribeiro et al., 2018[38]

regeneration, and help provides the correct stimulus to pharmaceutical drugs. The research on 4D printing is going to create a blood vessel, which can release substance as per patient body temperature. Significant contributions of the study are as under:

- 4D is an emerging technology that uses additive manufacturing technique that prints smart material from the input of CAD digital model
- As compared to 3D printing, this technology adds one more dimension of time to the product
- In orthopaedics, 4D printing is used to print smart orthopaedics implants/parts which can change their shape after implanting in the patient with respect to time and temperature
- This technology is beneficial to print customised, smart, flexible and high-performance part to meet the ongoing orthopaedics demand
- There are various smart materials which could be used in 4D printing technology, and these include Shape memory alloys, Electroactive polymers, Shape memory polymers, Magnetic shape memory alloys, Smart inorganic polymers, Electro-responsive polymers, Temperature responsive polymers, Photoresponsive polymer and Smart hydrogels
- Major advancements in orthopaedics provided by 4D printing are self-assembled orthopaedics implants, Knee prostheses, Spinal implants, Acetabular cups, Smart scaffolds, Tissue engineering, Living cells, Smart stents, Surgical implantation, Bone graft, development of biomedical splints and Better solution of children
- In future, this technology will provide more advancements in orthopaedics as compared to 3D printing

8. Limitations

Commercially, 4D printing is still at the stage of research and development. Limited numbers of smart materials are available, which can be used for part printing by this technology. There is a requirement of more research and development to commercially available to orthopaedics and clinical outcomes. This technology is at the beginning stage and will apply its potential capability to create advancements in orthopaedics. Smart materials used in this technology are costly and are not readily available in the market. In the current scenario, this technology is commercially available to a limited field, and many people do not have proper awareness about this technology. Sometimes, this creates risk when a printed part does not behave as per the requirements, or may not change the shape. Orthopaedics parts printed by this technology cannot claim original or even near to original and do not do perform precise function. Thus, researchers, technologists and doctors need to take this multi-disciplinary and interdisciplinary area for making the life of patient better.

9. Future scope

In future, the demand for 4D printed orthopaedics implants will increase for the full range of applications. This will drive a significant transformation in the orthopaedics field. A doctor could apply this technology into a neonatal intensive care unit. They can quickly develop a smart heart valve, which can work as per the required flow of the blood in the heart. 4D printing will be applied in research laboratories and many other specialist

Table 2
Significant advancements of 4D printing in orthopaedics.

S No	Advancements	Description	References
1	Self-assembled orthopaedics implants	• 4D printing can provide exciting changes by creating self-assembled smart orthopaedics implants using smart materials • These implants may have a lower risk of infection after implanting in the patient body • Having precise, accurate and customised approach with modified surface properties • Smart orthopaedics implants can also be monitored for deformation or other changes	Piedade et al., 2019[7]; Tan et al., 2019[42]; Sinha, 2020[43]
2	Knee prostheses	• Knee prosthetic printed by this technology can improve patient comfort • These smart prosthetics have the capability to handle the movement of the knee in the desired manner • Revolutionised the orthopaedics field to manufacture various other smart prosthetics which can adopt/grow as per the patient body • This technology can effectively create on-demand dynamically controllable shapes with the time dimensions	Teoh et al., 2018[44]; Grinberg et al., 2019[45]
3	Spinal implants	• Surgeons can use this technology for the printing of spinal implants which is helpful to treat deformity and strengthen the spine • Smart spinal implants could be used for the treatment of fracture, degenerative disc disease and scoliosis • This technology is efficient for the treatment of tumour in the patient neck • Customised perfect fitted spinal implants can successfully restore the stability of the spine for a patient	Schwartz et al., 2019[46]; Grinberg et al., 2019[45]
4	Acetabular cups	• 4D printing has the capability of manufacturing acetabular cups that can successfully be placed in the hip socket • Revolutionised for massive bone defect treatment of pelvis with better performance • Acetabular cups printed by this technology can be used for long term clinical outcomes • Having design freedom which enables the production of complex porous structure with required features	Wong et al., 2015[47]; Manganaro et al., 2017[48]
5	Smart scaffolds	• 4D printing is an emerging technology used to manufacture scaffolds with smart materials which imitate the dynamic responses of tissues • This adapts to the changes in the properties with respect to the environment • This technology uses smart nano bioink to create scaffolds efficiently • Provide feasibility for the stimulation of neural stem cell behaviours • Capability to create complex microarchitecture having a 4D transformation	Shin et al., 2017[49]; Ahadian and Khademhosseini, 2018[50]
6	Tissue engineering	• 4D printing can successfully be used in tissue engineering due to its extensive capability of temperature change in a controlled manner • Used for organs and tissue regeneration using self-healing hydrogels • These tissues have a great ability to fold and controlled with the effect of light • Used for replacement of damaged tissues during surgery and drug delivery	Tamay et al., 2019[10]; Miao et al., 2019[51]
7	Living cells	• 4D printing could also be used for the printing of cells for bone tissue engineering • These cells are used to support the growth of human bones • Helpful for the bone-implant to increase reliability and functions • A structure created living cells could successfully replace human tissue	Gao et al., 2016[52]; Miao et al., 2020[53]
8	Smart stents	• Stents having complex geometry and these also required the flexibility which can quickly fulfil by this technology • This can change the diameter, shape after implanting in the patient body concerning patient temperature • Useful to print stents rapidly to perform successful surgery • Increase success rate after the insertion of stents during operation	Zhang et al., 2019[6]; Shie et al., 2019[54]
9	Surgical implantation	• 4D printed external airway splints can be used effectively for surgical implantation • This splint can design in a way which can be grown and resolved the required issues • It enhanced the critical properties and also useful for nerve tissue regeneration	Haleem and Javaid, 2019[55]; González-Henríquez et al., 2019[56]
10	Bone graft	• This technology is used to create bone graft using biocompatible hydrogels • Used to develop a nervous and microvascular system to create bone graft substitute • Also applicable for the generation of 3D printed structure of cell-laden and functionalisation of cells and tissue concerning the time	Zarek et al., 2017[57]; Qasim et al., 2019[58]
11	Development of biomedical splints	• Easily print biomedical splint which can adopt changes in the environment • Potential to print programmed biological materials used for personalised medical and treatment of various other diseases • Printed splint could absorb and hold open airway in newborn babies for their good health	Ge et al., 2016[59]; Bodaghi et al., 2017[60]
12	A better solution for children	• Provide innovative solution which still growing by creating smart implants of required body parts • Researchers have applied 4D printing for facial reconstructions and rebuilding ears using smart biomaterials • Provide a flexible solution to adopt the natural growth of children	Miao et al., 2017[61]; Melocchi et al., 2019[62]

companies. It will create artificial organs which can be transplanted in the patient body. In future, this technology will be used to print footwear which can be adjusted as per the walking, running and playing requirement. Researchers will be successfully applying this technology for bioprinting applications of organ printing which can reduce the shortage of donor. In the future automobile, this can explore its potential to manufacture new components which can reduce fuel consumption. 4D printing can be used for every aspect of manufacturing flexibly. The possibility of this technology will remain endless, which has the potential to change the world.

10. Conclusion

4D printing technology provides positive effects in the field of orthopaedics. There are different types of smart materials available in the market and could be used by 4D printing. It uses responsive materials have properties of expansion, folding, twisting, colour change, contraction and degradation. These materials are smart and intelligent, having unique self deformation property. Doctors can make better treatment of any abnormalities regarding orthopaedics. This innovative technology will solve various issues in the real world. It rapidly manufactures the self-assembled orthopaedics implants, knee prosthetics and spinal implants as per the exact match of the patient. Smart scaffold manufactured by this technology is used for bone tissue engineering. It has many future opportunities in research and development, which was not previously possible by the traditional 3D printer. This technology will provide new technological advancements and a platform by the development of smart and programmable materials. It can manufactures orthopaedics parts having appropriate physical and chemical properties in a well-controlled manner.

Declaration of competing interest

There is no conflicts of interest.

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