3D-Printed Objects for Multipurpose Applications

Nayem Hossain, Mohammad Asaduzzaman Chowdhury, Md. Bengir Ahmed Shuvho, Mohammad Abul Kashem, and Mohamed Kchaou

Submitted: 4 November 2020 / Revised: 24 February 2021 / Accepted: 4 March 2021 / Published online: 26 March 2021

3D printing is a popular nonconventional manufacturing technique used to print 3D objects by using conventional and nonconventional materials. The application and uses of 3D printing are rapidly increasing in each dimension of the engineering and medical sectors. This article overviews the multipurpose applications of 3D printing based on current research. In the beginning, various popular methods including fused deposition method, stereolithography 3D printing method, powder bed fusion method, digital light processing method, and metal transfer dynamic method used in 3D printing are discussed. Popular materials utilized randomly in printing techniques such as hydrogel, ABS, steel, silver, and epoxy are overviewed. Engineering applications under the current development of the printing technique which include electrode, 4D printing technique, twisting object, photosensitive polymer, and engines are focused. Printing of medical equipment including artificial tissues, scaffolds, bioprinted model, prostheses, surgical instruments, COVID-19, skull, and heart is of major focus. Characterization techniques of the printed 3D products are mentioned. In addition, potential challenges and future prospects are evaluated based on the current scenario. This review article will work as a masterpiece for the researchers interested to work in this field

Keywords characterization, challenges, 3D printed, medical applications, printing applications, simulation

1. Introduction

3D objects are created by the successive layers of material controlled digitally by three-dimensional printing. Complex parts which are time-consuming and expensive by traditional methods can be produced in less time and at low cost by 3D printers. Both prototype and functional parts are produced rapidly and accurately without making any waste. It is also considered sometimes as a new industrial revolution (Ref 1).

This invited article is part of a special topical focus in the *Journal of Materials Engineering and Performance* on Additive Manufacturing. The issue was organized by Dr. William Frazier, Pilgrim Consulting, LLC; Mr. Rick Russell, NASA; Dr. Yan Lu, NIST; Dr. Brandon D. Ribic, America Makes; and Caroline Vail, NSW Carderock.

Nayem Hossain, Department of Mechanical Engineering, International University of Business Agriculture and Technology (IUBAT), Dhaka 1230, Bangladesh; and Department of Mechanical Engineering, Dhaka University of Engineering & Technology (DUET), DUET, Gazipur 1707, Bangladesh; **Mohammad Asaduzzaman Chowdhury**, Department of Mechanical Engineering, Dhaka University of Engineering & Technology (DUET), DUET, Gazipur 1707, Bangladesh; **Md. Bengir Ahmed Shuvho**, Department of Industrial and Production Engineering, National Institute of Textile Engineering and Research (NITER), Savar, Dhaka 1350, Bangladesh; **Mohammad Abul Kashem**, Department of Computer Science and Engineering, Dhaka University of Engineering & Technology (DUET), DUET, Gazipur 1707, Bangladesh; and **Mohamed Kchaou**, Department of Mechanical Engineering, College of Engineering, University of Bisha, Bisha 67714, Kingdom of Saudi Arabia; and Laboratory of Electromechanical Systems (LASEM), National Engineering School of Sfax, University of Sfax, 3038 Sfax, Tunisia. Contact e-mails: asadzmn2014@yahoo.com and asad@duet.ac.bd.

For the ease of consolidation, early additive manufacturing applications emphasized on the use of polymers either through a photopolymerization or thermal process (Ref 2, 3). Because of technological transmission, there has been an increased uptake of metal-based additive manufacturing used as a prototyping tool to make end products (Ref 4). The main technologies for 3D printing are direct metal laser sintering, electron beam melting, FDM using a metal-filled polymer filament, and directed energy deposition (Ref 5-8).

Various materials and techniques are utilized in the 3D printing process. The top-down lithography process is one of them that includes two-photon polymerization, focused ion beam, and electron beam lithography, and therefore, it can produce precise patterning with the desired shape using a layer-by-layer profile (Ref 9-11). Fused deposition of polymer is another type of popularly used 3D printing process where machines are not expensive and easy to operate (Ref 12). Both conventional polymers and polymer composites containing solid particles can be used to print. Among the commonly used materials, hydrogel materials are commonly used for their capacity as bioinks in a 3D printing system for cell printability and encapsulation (Ref 13). Composite materials are employed in 3D printing for the fabrication of complex geometries because of having superior thermal, mechanical, and electrical properties (Ref 14-16). Besides, having the ability to respond to external stimuli like water, temperature, and light smart materials has significant applications in 3D printing (Ref 17-20).

Applications of 3D printing in medical, industrial, automotive, construction, architecture, electronics, aerospace, and decorative sectors are abundant. Complex composite tissue constructs are created by 3D printing in a layer-by-layer fashion where cell-laden hydrogels are precisely placed (Ref 21, 22). Battery components including a separator, electrodes, current collector, and solid polymer electrolyte are customized within the final optimized design 3D object through the direct incorporation of microbatteries and electronics (Ref 23-27). Within a short time, complex-shaped microstructures

and geometries can be built (Ref 28, 29). By using microelectromechanical systems microstructured metals are being manufactured from ceramics (Ref 30, 31). Conductive fillers made conductive nanocomposites manufactured by 3D printing have potential applications in the fields of robotics, tactile sensors, and microelectromechanical systems (Ref 32–35).

Application of additive manufacturing particularly in medical science and medicine shows tremendous improvement (Ref 36). Current research on additive manufacturing for medical applications is focused on four main areas, and the areas are: (1) pathological organ models manufacturing research to aid surgical treatment analysis and preoperative planning (Ref 37); (2) personalized manufacturing research to make permanent nonbioactive implants; (3) local bioactive and biodegradable scaffolds fabrication research; (4) organs and tissues printing research for complete life function (Ref 38–40). To manufacture medical equipment, additive manufacturing makes the best use of raw material with minimum waste, make better mechanical integrity and the geometrical accuracy become satisfactory. The metals used in medical applications are typically titanium, titanium oxide, stainless steel, titanium nitride, zirconium oxide, carbon nitride, and cobalt chromium alloys (Ref 41, 42).

2. Mechanisms of 3D Systems

2.1 Methods

Manufacturing of 3D products by 3D printers is performed by various methods. The fused deposition is considered one of the most popular and economical methods where thermoplastic polymers are used for the preparation of filament suitable for a 3D printer (Ref 43). In this method, cheap complicated items can be produced with reduced waste (Ref 44). Thin layers of melted thermoplastic material are deposited in this process in many successive passes for making the desired 3D object where the computer controls a heated nozzle in the direction of the XYZ-axis. After extrusion, the thermoplastic material instantaneously cools down to be deposited and the material is heated only a few degrees above its melting temperature. Transparent parts with photo-induced layer can be produced allowing UV absorbers having the thickness typically around 50–200 μm (Ref 45).

Due to the advantages of low cost, short cycle time, and high precision to manufacture complex-shaped ceramic parts stereolithography 3D printing is widely employed. Stereolithography 3D printing has produced SiO_2 , Al_2O_3 , ZrO_2 , bioceramics, and lots more. In order to make optical mirrors in recent years, 3D printing has been applied for the manufacturing functions of ceramics and ceramics matrix composites. The stereolithography 3D printing process is rarely observed in the studies to make SiC ceramic and its optical components (Ref 46).

The laser beam is a subset of powder bed fusion where solid objects are created by heating solid particles. In the process, they are also fused together at their surfaces. Carl Deckard developed the technology based on a neodymium-doped yttrium aluminum garnet in 1984. The printer made many prototypes by acrylonitrile butadiene styrene (ABS) and thermoplastic polymer (Ref 47).

Digital light processing is another popular 3D printing method where complex-shaped ceramic parts are fabricated. Personalized structured ZrO_2 ceramic teeth having a good mechanical property, biocompatibility, and strong potentiality in the field of oral restoration are prepared by this method. This method also produced fine lattice structural titanium dioxide ceramic and porous BN- SiO_2 ceramics (Ref 48).

Metal transfer dynamics are investigated in depth in the wire feeding-based electron beam 3D printing process. Here the experiments are combined with novel modeling of the heat transfer and molten flow behaviors. Experimental and simulation results recognize different metal transfer modes and are revealed quantitatively. A simple theory determines the relationship between the mode good for forming quality and the process parameters (Ref 49).

2.2 Materials

Many different materials can be used in 3D printing to manufacture products. In medical science hydrogel materials for example collagen, gelatin, and alginate are commonly used as bioinks. Collagen hydrogel is the most abundant natural polymer found in mammalian tissue. It has the capability of providing a favorable microenvironment because of having a native extracellular matrix, and for this, it is commonly utilized for the regeneration of vasculature, bone, liver, and nerves (Ref 50).

ABS (acrylonitrile butadiene styrene) is used in 3D printing for mechanical and electrical works. Sezer et al. (Ref 51) utilized ABS matrix MWCNTs filler nanocomposites in their research of additive manufacturing. In the process ABS with MWCNTs was compounded with a twin-screw microextruder keeping the screw speed at 100 rpm in the dispersion process. To avoid degradation of the ABS 240 $^{\circ}\text{C}$ temperature was kept constant in the extruder for 5 minutes to ensure complete melting and mixing. Maintaining the weight percentage 1, 3, 5, 7, and 10, the MWCNT/ABS nanocomposite samples were prepared.

In order to satisfy the mechanical properties steel is reinforced with other materials to give higher strength. Li et al. (Ref 52) reinforced steel microcable with a geopolymer composite in his 3D printing research for the mechanical improvement of the product. 1.2 mm of diameter continuous steel microcable having 7 shares and each share had 19 strands was extruded from the print head along with the geopolymer. Steel microcable small curvature was ensured by using a 15-mm-diameter round nozzle during printing. After attempting several times, the horizontal printing speed and the steel microcable entering speed are kept equal.

Silver is extensively used in 3D printing to print dental materials. Liao et al. (Ref 53) utilized silver nanoparticles with zirconium oxide to strengthen dental base composites in 3D printing. In the process they utilized, desired materials were synthesized at two different stages. In the first stage, nanosilver-loaded zirconium phosphate was salinized under an acidic condition with MPS. 4.0 g 6S-NP3 and 150.0 g deionized water were mixed in a clean beaker for ultrasonic dispersion for 1 h. Meanwhile, with constant speed injection, 1.0 g acetic acid, and 50.0 g deionized water were dropped together. The suspension was charged with a machine stirring (200 r/min) into a 500-mL four-neck flask and heated to 30 $^{\circ}\text{C}$ followed by adding into the system in 1 h with the mixture of MPS and cyclohexane. The mixture temperature reached 80 $^{\circ}\text{C}$ and maintained the reaction

for 1.5 h. Using acetone M-6S-NP3 (methyl nanosilver-loaded zirconium phosphate) was created through extraction, and then, the solution was dried in the vacuum oven for 12 h at 80 °C. At the next stage, M-6S-NP3 was grafted with PMMA where free radical polymerization was used. 1.0 g M-6S-NP3 was dispersed in a 250-mL four-neck flask in 50.0 g xylene with the help of a stirring machine and then dispersed ultrasonically for 0.5 h. Then, under nitrogen atmosphere, 10.0 g MMA and 0.1 g BPO initiator were added. In a water bath, the mixed suspension was kept stirring at 80 °C. The P-6S-NP3 was obtained after 8.0-h polymerization through centrifugal separation and extraction with acetone and then dried for 12 h at 80 °C in a vacuum oven.

Epoxy materials give desirable properties with improved mechanical, thermal, and chemical properties to the 3D-printed materials. For extrusion-based 3D printing, nanoclays can be used in epoxy or short fiber composite inks for the purpose of direct-write (DW) additive manufacturing (AM) so that it can be imparted in nearly ideal rheological properties. In general, significant effort is given so that polymer matrix composited can be used in 3D printing, and rapid progress is observed in epoxy-based composite materials. Hmeidat et al. (Ref 54) et al. used epoxy nanocomposites for making high-strength 3D-printed materials. With appropriate amounts of nanoclay or fumed silica, the process inks were prepared by mixing the epoxy resin in 185-mL plastic containers using a centrifugal planetary Speed Mixer. Using 30 g of Epon 826 resin and 1.5 g of the curing agent (VS03) six formulations, plus the control, were prepared. Under vacuum at 0.1 atm for 60 s, the contents were mixed at 1700 rpm. After 60 seconds of mixing at 1700 rpm and 0.1 atm, the nanofiller was added. Then, they scraped the container with a spatula so that the nanoclay can be kept the mixture completely dispersed and bubble-free by mixing for an additional 60 s at 1800 rpm and 0.1 atm.

3. Multi-Applications of 3D Systems

3.1 Printing Applications

Numerous applications are visible of 3D printing in printing applications. The 3D-printed electrode is one of them which can be printed both vertically and horizontally. The incorporation of smart materials or programmable materials that have the stimuli in temperature, water and light in 3D printing has brought a new dimension called 4D printing (Ref 55). Sun et al. (Ref 56) fabricated 4D material by a continuous printing technique. Localized thermal recovery is achieved after different loadings of polyplasticized material mentioned in Fig. 1. During the fabrication process, PLA pellets were first dried for 24 h at 80 °C. 10 wt.% and 30 wt.% were used then as a plasticizer by melt-blending to PLA using a microcompounder for 10 min at 170 °C and 100 RPM. They fabricated the 3D-printable PLA/PEG filaments by attaching an automatic roller, after compounding at the end of the compounder. The 4D components were fabricated by a customized 3D FDM printer using a standard 0.3-mm nozzle keeping the nozzle temperature of 180 °C. Reshapable arc-shaped components were printed later by compression force into a flat configuration.

Products with rotational and twisting capabilities are manufactured with the help of 3D printing. Tuning elements having to twist and rotational bistable structures have been

fabricated by Jeong et al. (Ref 57). In the fabrication procedure, they used the polyjet process in a Stratasys multi-material 3D printer where ultraviolet light was used for jetting the photopolymer ink droplets. They also created fine features with about 50 µm resolution in the plane and 15 µm in thickness by the process. Before importing into the Stratasys printer geometric design was first created using CAD software. Without postassembly and using a consolidated design they fabricated twisting and rotational bistable components. They used some special joints that allowed 3D printing of the whole components such as twisting components used ball joints, rotational used pin joints.

3D printing has the advantages of producing polymeric material over other methods. Transparent, light and photosensitive polymer material has been fabricated by Wang et al. (Ref 58). A rigid, nearly colorless material exhibiting dimensional stability with the trade name VeroClearRGD 810 resinous material has been chosen for the experiment. By using AutoCAD cylindrical and dog-bone-shaped specimens were created at first. The specimen was printed by the Object Studio program then.

Engines for optical communication are fabricated by 3D printers. Hybrid multi-chip assembly of optical communications engines has been fabricated by Bleicher et al. (Ref 59) by in situ 3D nanolithography. In the process, they fabricated all PWB structures where a modified commercial two-photon lithography system was utilized. An fs laser having a pulse length of 100 fs along with a repetition rate of 80 MHz has been used as a lithography light source. The proprietary control software was used for allowing the precise localization of coupling interfaces and automated the PWB fabrication with high shape fidelity used to equip the lithography system.

3.2 Medical Applications

The invention of 3D printing has brought a new era for medical science. Numerous materials are being printed for the applications in this field. In the field of tissue engineering, artificial tissues are being developed by controlled deposition and cells (Ref 60). Kang et al. (Ref 57) synthesized bioprinted tissue by depositing cell-laden hydrogels together with a synthetic biodegradable polymer. That was accomplished in the following ways: they designed multi-dispensing modules for delivering different cell types and polymers in a single construct, they made a carrier material to deliver cells in a liquid form to discrete locations in the 3D structure, they designed a sophisticated nozzle system where the resolution was 2 µm for biomaterials and 50 µm for cells, they linked together cell-laden hydrogels after passage through the nozzle system, they printed an outer sacrificial acellular hydrogel mold simultaneously and dissolved after acquiring enough rigidity by tissue construct to retain its shape, and they created a lattice of microchannels that could nutrient and diffuse oxygen into the printed tissue constructs.

Hybrid microcaffolds are being produced with the help of 3D printing. Tan et al. (Ref 61) applied a new biofabrication strategy called hybrid microcaffold-based 3D bioprinting of multicellular constructs that could produce products having compressive strength. High specific surface areas are provided by the highly porous microcaffolds to get the anchorage-dependent cells capable of attaching infiltrate and grow before extrusion-based printing. That property will expand the cells seeded on the microspheres where it will be exploited in stirred

Fig. 1 Thermal recovery of 4D functionally graded model (Ref 56). Licensed under Creative Commons Attribution 4.0 International Public License, <https://creativecommons.org/licenses/by/4.0/>

Fig. 2 Schematic illustration of the bioprinting process (Ref 58). Licensed under Creative Commons Attribution 4.0 International Public License, <https://creativecommons.org/licenses/by/4.0/>

or perfused culture and no passaging will take place from cell-laden microspheres (CLMs). Together with thin hydrogel encapsulation, those CLMs could act as a bioink material for 3D bioprinting when the CLMs were lubricated by the printing hydrogel and glued after printing upon gelation shown in Fig. 2.

Bioprinted models are another product of 3D printing. 3D bioprinted model capable of evaluating the effect of stiffness on neuroblastoma cell cluster dynamics and behavior has been fabricated by Monferrer et al. (Ref 62). For the fabrication purpose, required cells were collected and expanded in a growth medium. Cells were cultured and trypsinized to create

the bioinks. With the prepolymer solution, the resulting pellet was resuspended and loaded in a bioprinting syringe. Morley et al. (Ref 63) fabricated 3D bioprinted structural elements. In the fabrication process, an ionizable comonomer is prepared by cross-linking polyacrylamide microgels with 17 mol.% methacrylic acid. Another solution was prepared in 490 mL ethanol by 8% (w/w) acrylamide, 2% (w/w) methacrylic acid, 1% (w/w) poly(ethylene glycol) diacrylate ($MW = 700 \text{ g mol}^{-1}$), and 0.1% (w/w) azobisisobutyronitrile. The solution was placed into a preheated oil bath after sparging with nitrogen for 30 min at 60 °C. The reaction mixture was heated after forming white precipitation for 4 h. Then the microparticles were triturated after filtration with 500 mL of ethanol overnight. The solids were collected again and dried. The purified microgel powder was dispersed, mixed, and neutralized. For each type, the microgel 3D printing is prepared along with the culture medium. Using 12-well plates of single 35-mm Petri dishes, fabrication of microbeams was enabled.

3D printing also helps in a bone generation. Bioceramic scaffolds stimulate pediatric bone regeneration has been fabricated by Wang et al. (Ref 64) with the help of 3D printing. At the beginning of the process for the visualization of the rabbit's calvarium, a 13-mm skin incision was created. For exposing calvarial bone periosteum and soft tissue were dissected. Using 10 mm diameter trephine defects were created. Then the defects were repaired with either 3D-printed scaffolds loaded with 1000 μM DIPY or bone graft where a fit-and-fill method was used. Proper inset was ensured when the violation of the dura mater was avoided, and the primary stability of the scaffold was obtained. Then calvarial bone graft was created by the immersion of trephined calvarium in saline solution. On the right aspect of the midface, a 13-mm skin was created in the alveolus. The soft tissue, alveolar ridge, and the maxillary suture and periosteum were dissected for the visualization of the maxilla. 3D-printed template was produced by either 3D-printed scaffold loaded with 1000 μM , DIPY or bone graft defects were repaired again with the help of a fit-and-fill method so that reconstruction primary stability and avoiding violation of the maxillary sinus membrane were ensured. Before creating the maxillary defect, an alveolar bone graft was created by harvesting radial bone from the right rabbit forearm and 10-mm longitudinal incisions were made.

Innovative approaches like incorporating antibiotics into 3D-printed constructs are done by 3D printing. The common applications are medical implants, prostheses, and surgical instruments. Increased surface area for drug distribution, sequential layers of antibiotics and the ability to rapidly fabrication is permitted by 3D-printed antibiotic-impregnated devices. Table 1 shows the advantages and disadvantages of inkjet, fused deposition modeling, and stereolithography 3D printing techniques to incorporate antibiotics into 3D-printed constructs, and a short summary of recent bioprinting is shown in Table 2.

There has been a shortage of personal protective equipment (PPE) in many countries of the world due to the current COVID-19 pandemic where 3D printing is playing a good role. Breathing device is one of the most wanted devices for patience in many countries. As the normal production and the key pieces of PPEs cannot match the current demand, other means of manufacturing for these items are being practiced in many countries. Face masks, face shields, Venturi valves, and other oxygen masks are examples of 3D-printed products. Due to additive manufacturing certified medical devices have been delivered to the market in short possible times (Ref 76).

Based on the patient's situation additive manufacturing allows to print implants. More affordable and more precise alternative to bone cement have been developed by Dinesh et al. (Ref 77) for individualized implants. By the help of a CT scanning image, the team of Moiduddin et al. (Ref 78) created a 3D digital model of patient's skull and printed the model and implant where they used fused deposition modeling method. The printed implant had similar properties to the actual bone. Skull defects can be reconstructed by using a synthetic material known as hyperelastic bone by 3D printing method. This synthetic material contains bone mineral hydroxyapatite as well as common polyglycolic acid biocompatible material. For being lattice network, hyperelastic bone can be reconstructed allowing new bone material to grow (Ref 36).

In the field of cardiology, additive manufacturing is showing its excellence. For the communication of doctors with patients in some unique medical situations, patient's heart can be created by 3D printing. Additive manufacturing is relatively quick and cost-effective method to produce 3D anatomical heart models to develop surgical planning as well as treatment outcomes. Similar models can also be used in medical training program to train surgeon (Ref 79). For the development of vascular stents, additive manufacturing can also be applied to manage blood flow obstruction. On-demand and custom-fit can be created by this method for each patient. Thicker or thinner design can be

created by customizing of stents around stressed or unstressed region of a vessel in order to increase blood flow (Ref 80). 3D printing is also useful in cardiology to design scaffolds. Melt extrusion technique is applied to produce this type of scaffolds that enable heart regeneration following a heart attack (Ref 81).

The production of orthopedic aids is now more accurate, more automated as well as less expensive due to the application of additive manufacturing in making these aids. A method has been described by Molnar and Morovi (Ref 82) where a custom-fit orthopedic corset has been produced for lower back support. In the method, a digital model was created by scanning the patient. CAD software has been used to prepare a custom-fit orthopedic corset using the data from the scan. Then, by applying the fused deposition method the corset was printed (Ref 83). Polylactic acid and polyethylene terephthalate glycol were used to make the corset because the materials needed to be both printable and biocompatible.

4. Simulation and Characterization of 3D Structure

3D-printed materials are simulated and characterized by different techniques. Park et al. (Ref 75) performed an SEM test to characterize 3D-printed electronics made of conductive cellulose composites with a low porcelain threshold. Embedded conductive fillers which are in an insulative polymer matrix are shown in images. Figure 3(a) with a higher volume fraction is compared with Fig. 3(b) having a lower volume fraction. Clusters forming the localized percolation networks are seen in Fig. 3(b). This shows a well-matched resistivity change result in the simulation. In between Fig. 3(a) and (b), comparatively higher resistivity is observed in Fig. 3(a).

EDS spectrum analysis is used to show the chemical composition of the 3D-printed material. EDS analysis of the additive manufactured 3D nanoarchitect metals is performed by Andrey Vyatskikh et al. (Ref 84). The spectrum taken from a beam section shows the chemical composition as 91.8 wt.% Ni, 5.0 wt.% O, and 3.2 wt.% C shown in Fig. 4(a). TEM analysis is performed to show the presence of nanoparticles in the manufactured products. Hyunwoo Yuk et al. (Ref 85) performed the TEM analysis in 3D printing of conducting polymers. The image shows the dilute dispersion of nanofibrils in the solution shown in Fig. 4(b).

Different mechanical tests are also performed in the 3D-printed structures. Bending with bare hand and simple radial

Table 1 Advantages and disadvantages of inkjet, fused deposition modeling, and stereolithography 3D printing techniques to incorporate antibiotics into 3D-printed constructs (Ref 65)

Process	Inkjet	Fused deposition modeling	Stereolithography
Material choice	Limited	Wide variety	Limited
Thermal degradation of added antibiotic	Only if postprocessing involves heating	Possible	Not applicable
Ultraviolet degradation of added antibiotic	Not applicable	Not applicable	Possible if drugs used are ultraviolet sensitive
Mechanical reduction with adding antibiotic	None in one study	Possible	Unknown

Table 2 A short summary of recent bioprinting studies

Materials	Method	Application	Remarks	Ref.
Nanocellulose	Extrusion	Wound dressing	The nanocellulose bioink was utilized for printing 3D porous structure. Also studied that nanocellulose did not support bacterial growth	(Ref 66)
Human corneal epithelial cells (HCECs)/collagen/gelatin/alginate hydrogel	Extrusion	Tissue Engineering	The 3D-printed hydrogel network with microporous structure and interconnected channels is stable and acquired high cell viability (more than 90%). The developed HCECs exhibited a greater cytokeratin 3 (CK3) and higher proliferation, signifying that newly developed technique may help to enhance the alginate bioink system for the application of 3D printing in tissue engineering.	(Ref 67)
Nanofibrillated cellulose (NFC), alginate	Extrusion	Bioprinting of living tissues and organs	Investigated that the nanocellulose-based bioink is compatible hydrogel for 3D biofabrication with living cells.	(Ref 68)
Alginate, GelMA, HUVECs	Extrusion	Tissue engineering	The low-viscosity cell-responsive bioink encourages cell migration and alignment within each fiber organizing the enclosed cells.	(Ref 69)
Type I collagen and chitosan agarose blends, human bone marrow derived mesenchymal stem cells (hMSCs)	Extrusion	3D-printed mesenchymal tissues	The conjugation of type I collagen to agarose with varying ratios is possibly a suitable bioink for a broad range of 3D-printed mesenchymal tissues.	(Ref 70)
Polycaprolactone (PCL)	Combined extrusion-based cryogenic 3D printing (ECP)	Tissue Engineering	The ECP scaffolds promoted the adhesion and proliferation of MCT3T-E1 cells with well-spread morphology on the porous filaments.	(Ref 71)
Polyester (4-hydroxyphenethyl 2-(4-hydroxyphenyl)acetate (HTy))	Extrusion	Tissue Engineering	The novel polymer platform with tunable functional ability could be utilized for 3D bioprinting scaffold and biodegradable devices with tailored bioactive and mechanical properties for a wide range of medical applications including scaffolds for bone production and bone fixation devices	(Ref 72)
Poly(lactic acid/ polycaprolactone/ hydroxyapatite (PLA/PCL/HA) composites.	Negative mold Indirect 3D printing	Bone Tissue Engineering	The 3D-printed structure showed that the composite scaffold with the PLA/PCL weight ratio of 70/30 obtained higher adjuvant properties in terms of viability, biocompatibility, and osteoinduction	(Ref 73)
Gelatin/carboxymethylchitin/hydroxyapatite composite	Extrusion	Bone Tissue Engineering	The scaffolds are spongy in nature in a wet state, therefore, applying them potential implants for bone cavities with a small opening.	(Ref 74)
Hyaluronic acid and gelatin	Extrusion	Primary liver constructs with high viability	The hydrogel bioink system could be a potential versatile technique for bioprinting of a wide range of tissue construction	(Ref 75)

(a)

(b)

Fig. 3 Computational design and percolation evaluation of 3D conductor and experimental percolation threshold of 3D conductor (a) SEM image of 0.3 Vol. % AgNW in CMC, (b) SEM image of 1.9 Vol. % AgNW in CMC (Ref 75). Licensed under Creative Commons Attribution 4.0 International Public License, <https://creativecommons.org/licenses/by/4.0/>

direction compression are among them. The shape was recovered after applying compression and bending force to the original state for the 3D-printed 2L-P MFT construct without breaking down as seen in Fig. 5(e). For each case of the MFT constructs the ultimate strength was calculated based on the stress–strain curves, and the results were 2.16 ± 0.6 , 8.60 ± 0.7 , 7.15 ± 1.3 , and 13.50 ± 1.3 , respectively (Fig. 5(f, g)). The calculated Young's modulus was found for each case as 25.32 ± 10.02 , 66.43 ± 2.97 , 66.94 ± 5.6 , and 86.86 ± 14.63 MPa, respectively, shown in Fig. 5(h). The calculated ultimate strengths were 2.43 ± 0.45 , 3.76 ± 0.07 , 6.92 ± 1.34 , 7.20 ± 0.1 MPa, respectively, for the MFT constructs (Ref 86).

A straight microchannel was fabricated in order to investigate the bonding quality having dimensions of 50 μm height, 200 μm width, and 4 cm length, and it was tested accordingly. For the appearance and growth of Saffman-Taylor fingers, the device performance has been monitored until it becomes stable, known as “inflation stability” (Fig. 6a). To identify the channel behavior the results are presented in a 2D diagram at a given

(a)

(b)

Fig. 4 (a) Energy-dispersive spectroscopy (EDS) of fabricated metal nanostructures (Ref 84), (b) CryoTEM image of a pristine PEDOT: PSS solution (Ref 85). Licensed under Creative Commons Attribution 4.0 International Public License, <https://creativecommons.org/licenses/by/4.0/>

pressure, as shown in Fig. 6(c). According to the results, the interface between the 3D-printed part and PMMA sheet became leakproof because of achieving holding strength of the double-coated adhesive tape. Shear rate distribution was also evaluated across a line parallel to the channel width as Fig. 6(b). The safe zone for performing inertial microfluidic experiments is seen in the green area in Fig. 6(c). Experiments show that Saffman-Taylor fingers begin to appear when pressure is more than 82.6 psi. When it was run at high pressure in channels, any delamination or deformation was not observed (Ref 87).

5. Potential Challenges in Future

Future studies in 3D printing will likely involve the development of new printable metals for structural elements. Printing of large and bulk components can be focused. In order to enable strength, flexibility, and safety further research is required for the evaluation of the mixtures of materials and printing techniques. Comparatively less-expensive 3D printers

Fig. 5 Computational and experimental analysis of the mechanical characteristics of the wrinkle and the bellows' shapes. (a) Contour plot (0.2 MPa) radial-directional pressure and deformed configuration, (b) pressure results comparison at each point A, A', (c) bending moment (40 N.mm) contour plot, (d) bending moment results comparison at each point B, B', (e) 3D-printed recovering test of 2-layer pore construct, (f) stress-strain responses of the scaffolds (2-, 3-layer pore/nonpore), (g) ultimate strength comparison, (h) Young's modulus comparison (Ref 86). Licensed under Creative Commons Attribution 4.0 International Public License, <https://creativecommons.org/licenses/by/4.0/>

have lower resolution and poorer surfaces that can lead to increased cost due to post-processing requirements. Besides printers with lower tolerance are not suitable for manufacturing products for assembly works. Energy consumption, space, and setting requirement result in more cost in industrial machining. As a result, large production becomes more expensive in 3D printing compared to traditional machining (Ref 88). For the support of new applications in medicine, new printable and biocompatible material may be involved in the research. Research may also associate with the cost reduction in printing.

The field of 3D printing is still far away for the mass production of products to meet the demand of average customers. It has passed a long way in the last 2 decades through sophisticated printers that are too expensive to attract the nonspecialist. The environmental standards are not set to the equipment technology properly (Ref 89).

3D printing has several environmental impacts associated with the printing process. It has greater energy demand compared to the traditional machining processes. Volatile organic compounds, solvents, nanoparticles may pollute the environment. Toxicity emission from materials might harm

(a)

(b)

(c)

Fig. 6 (a) Analyzing the Saffman-Taylor finger criteria for the bonding quality in a microchannel versus various flow rates. (b) Shear rate distribution across a line parallel to the channel width. (c) The more the pressure, the faster the creation of Saffman-Taylor fingers (Ref 87). Licensed under Creative Commons Attribution 4.0 International Public License, <https://creativecommons.org/licenses/by/4.0/>

human health. Recycling of some materials is beyond processing. Some prospects are as well compared to other machining processes. It has greater raw materials efficiency and required less cutting fluid than milling. Green materials can be used as raw materials and thus protect the environment. Time consumption has decreased in prototype construction. Lower CO₂ emission is observed during lightweight construction. Spare parts and tools have a greater lifetime and adaptability to climate change. Clinical sectors are highly benefited because of bioprinting (Ref 90).

6. Conclusions

3D printing is a supportive advancement and probably the prime manufacturing technique in the future for different disciplines of engineering and medical science. It has shown dramatic development in recent years of using smart materials popularly known as 4D printing with conventional other materials. Incorporating nanomaterials to give strength and achieve desired mechanical properties is another milestone. Advancement in synthesizing biomaterials is another achievement probably beyond other conventional techniques. Though 3D printing has to pass a long way to be economical in industrial sectors, it has shown great advancement in a short period.

References

1. The third industrial revolution, The Economist, <http://www.economist.com/node/21553017> (2012)
2. X. Yan and P. Gu, A Review of Rapid Prototyping Technologies and Systems, *Comput. Des.*, 1996, **28**, p 307–318
3. A.K. Sood, R.K. Ohdar and S.S. Mahapatra, Parametric Appraisal of Mechanical Property of Fused Deposition Modeling Processed Parts, *Mater. Des.*, 2010, **31**, p 287–295
4. W.E. Frazier, Metal Additive Manufacturing: A Review, *J. Mater. Eng. Perform.*, 2014, **23**, p 1917–1928
5. A. Simchi, F. Petzoldt and H. Pohl, On the Development of Direct Metal Laser Sintering for Rapid Tooling, *J. Mater. Process. Technol.*, 2003, **141**, p 319–328
6. L.E. Murr et al., Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies, *J. Mater. Sci. Technol.*, 2012, **28**, p 1–14
7. B.E. Carroll, T.A. Palmer and A.M. Beese, Anisotropic Tensile Behavior of Ti-6Al-4V Components Fabricated with Directed Energy Deposition Additive Manufacturing, *Acta Mater.*, 2015, **87**, p 309–320
8. S. Masood and W. Song, Development of New Metal/Polymer Materials for Rapid Tooling Using Fused Deposition Modeling, *Mater. Des.*, 2004, **25**, p 587–594
9. J. Jeon, H.C. Floresca and M.J. Kim, Fabrication of Complex Three-Dimensional Nanostructures using Focused Ion Beam and Nano Manipulation, *J. Vac. Sci. Technol. B*, 2010, **28**, p 549–553
10. B.H. Cumpston et al., Two-Photon Polymerization Initiators for Three Dimensional Optical Data Storage and Micro Fabrication, *Nature*, 1999, **398**, p 51–54
11. C. Vieu et al., Electron Beam Lithography: Resolution Limits and Applications, *Appl. Surf. Sci.*, 2000, **164**, p 111–117
12. Wohlers Report: Additive Manufacturing and 3D Printing State of the Industry (Wohlers Associates, 2015). ISBN 978-0-9913332-1-9
13. W. Lee et al., Multi-Layered Culture of Human Skin Fibroblasts and Keratinocytes Through Three-Dimensional Freeform Fabrication, *Biomaterials*, 2009, **30**, p 1587–1595
14. F. Ning, W. Cong, J. Qiu, J. Wei and S. Wang, Additive Manufacturing of Carbon Fiber Reinforced Thermoplastic Composites using Fused Deposition Modeling, *Compos. B Eng.*, 2015, **80**, p 369–378
15. Q. Zhang et al., 3D Printing of Graphene Aerogels, *Small*, 2016, **12**, p 1702–1708
16. S.J. Leigh, R.J. Bradley, C.P. Purcell, D.R. Billson and D.A. Hutchins, A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors, *PLoS ONE*, 2012, **7**, p e49365
17. Z.X. Khoo et al., 3D Printing of Smart Materials: A Review on Recent Progresses in 4D Printing, *Virt. Phys. Prototyp.*, 2015, **10**, p 103–122
18. C. Liu, H. Qin and P. Mather, Review of Progress in Shape-Memory Polymers, *J. Mater. Chem.*, 2007, **17**, p 1543–1558
19. W. Huang, B. Yang, L. An, C. Li and Y. Chan, Water-Driven Programmable Polyurethane Shape Memory Polymer: Demonstration and Mechanism, *Appl. Phys. Lett.*, 2005, **86**, p 114105
20. H. Jiang, S. Kelch and A. Lendlein, Polymers Move in Response to Light, *Adv. Mater.*, 2006, **18**, p 1471–1475
21. S.V. Murphy and A. Atala, 3D Bioprinting of Tissues and Organs, *Nat. Biotechnol.*, 2014, **32**, p 773–785
22. T. Xu et al., Complex Heterogeneous Tissue Constructs Containing Multiple Cell Types Prepared by Inkjet Printing Technology, *Biomaterials*, 2013, **34**, p 130–139
23. X. Wang, M. Jiang, Z.W. Zhou, J.H. Gou and D. Hui, 3D Printing of Polymer Matrix Composites: A Review and Prospective, *Compos. Part B Eng.*, 2017, **110**, p 442–458
24. N. Savage, VOXEL8 3D Printing Mixes Materials, *Nature*, 2017, **545**, p S20–S20
25. D. Espalin, D.W. Muse, E. MacDonald and R.B. Wicker, 3D Printing Multifunctionality: Structures with Electronics, *Int. J. Adv. Manuf. Technol.*, 2014, **72**, p 963–978
26. K. Gnanasekaran et al., 3D Printing of CNT-and Graphene-Based Conductive Polymer Nanocomposites by Fused Deposition Modeling, *Appl. Mater. Today*, 2017, **9**, p 21–28
27. P.E. Delannoy et al., Toward Fast and Cost-Effective Ink-Jet Printing of Solid Electrolyte for Lithium Microbatteries, *J. Power Sources*, 2015, **274**, p 1085–1090
28. A.I. Shalhan, P. Smejkal, M. Corban, R.M. Guijt and M.C. Breadmore, Cost-Effective Three-Dimensional Printing of Visibly Transparent Microchips Within Minutes, *Anal. Chem.*, 2014, **86**, p 3124–3130
29. N. Bhattacharjee, A. Urrios, S. Kang and A.T. Folch, Upcoming 3D-Printing Revolution in Microfluidics, *Lab. Chip.*, 2016, **16**, p 1720–1742
30. B. Cappi, E. Özkol, J. Ebert and R. Telle, Direct Inkjet Printing of Si3N4: Characterization of Ink, Green Bodies and Microstructure, *J. Eur. Ceram. Soc.*, 2008, **28**, p 2625–2628
31. M. Vaezi, H. Seitz and S. Yang, A Review on 3D Micro-Additive Manufacturing Technologies, *Int. J. Adv. Manuf. Technol.*, 2012, **67**, p 1721–1754
32. U. Kalsoom, P.N. Nesterenko and B. Paull, Recent Developments in 3D Printable Composite Materials, *RSC Adv.*, 2016, **6**, p 60355–60371
33. X. Wei, D. Li, W. Jiang, Z. Gu, X. Wang, Z. Zang et al., 3D Printable Graphene Composite, *Sci. Rep.*, 2015, **5**(11181), p 1–7
34. S. Guo, K. Qiu, F. Meng, S.H. Park and M.C. Mcalpine, 3D Printed Stretchable Tactile Sensors, *Adv. Mater.*, 2017, **29**, p 1701218
35. J.T. Muth, D.M. Vogt, R.L. Truby, Y. Mengüç, D.B. Kolesky, R.J. Wood et al., Embedded 3D Printing of Strain Sensors Within Highly Stretchable Elastomers, *Adv. Mater.*, 2014, **26**, p 6307–6312
36. M.N. Nadagouda, V. Rastogi and M. Ginn, A Review on 3D Printing Techniques for Medical Applications, *Curr. Opin. Chem. Eng.*, 2020, **28**, p 152–157
37. A. Butscher, M. Bohner, N. Doeblin, S. Hofmann and R. Müller, New Depowering-Friendly Designs for Three-Dimensional Printing of Calcium Phosphate Bone Substitutes, *Acta Biomater.*, 2013, **9**(11), p 9149–9158
38. R.E. Saunders, J.E. Gough and B. Derby, Delivery of Human Fibroblast Cells by Piezoelectric Drop-on-Demand Inkjet Printing, *Biomaterials*, 2008, **29**(2), p 193–203
39. T. Xu, W. Zhao, J.M. Zhu, M.Z. Albanna, J.J. Yoo and A. Atala, Complex Heterogeneous Tissue Constructs Containing Multiple Cell Types Prepared by Inkjet Printing Technology, *Biomaterials*, 2013, **34**(1), p 130–139
40. B. Derby, Printing and Prototyping of Tissues and Scaffolds, *Science*, 2012, **338**(6109), p 921–926

41. W.C. Clem, S. Chowdhury, S.A. Catledge, J.J. Weimer, F.M. Shaikh, K.M. Hennessy et al., Mesenchymal Stem Cell Interaction with Ultra-Smooth Nanostructured Diamond for Wear-Resistant Orthopaedic Implants, *Biomaterials*, 2008, **29**, p 3461–3468
42. M. Rashed, M. Ashraf, R. Mines and P.J. Hazell, Metallic Microlattice Materials: a Current State of the Art on Manufacturing, Mechanical Properties and Applications, *Mater. Des.*, 2016, **95**, p 518–533
43. A. Maurel, S. Grugeon, B. Fleutot, M. Courty, K. Prashantha, H. Tortajada, M. Armand, S. Panier and L. Dupont, Three-Dimensional Printing of a LiFePO₄/Graphite Battery Cell Via Fused Deposition Modeling, *Sci. Rep.*, 2019, **9**, p 18031
44. H. Bikas, P. Stavropoulos and G. Chrysosolouris, Additive Manufacturing Methods and Modelling Approaches: A Critical Review, *Int. J. Adv. Manuf. Technol.*, 2016, **83**, p 389–405
45. J.W. Stansbury and M.J. Idacavage, 3D Printing with Polymers: Challenges Among Expanding Options and Opportunities, *Dent. Mater.*, 2016, **32**, p 54–64
46. G. Dinga, R. Hea, K. Zhangb, N. Zhou and H. Xu, Stereolithography 3D Printing of SiC Ceramic with Potential for Lightweight Optical Mirror, *Ceram. Int.*, 2020, **46**, p 18785–18790
47. A. Awad, F. Fina, A. Goyanes, S. Gaisford and A.W. Basi, 3D Printing: Principles and Pharmaceutical Applications of Selective Laser Sintering, *Int. J. Pharm.*, 2020, **586**, p 119594
48. F. Li, X. Ji, Z. Wu, C. Qi, J. Lai, Q. Xian and B. Sun, Digital Light Processing 3D Printing of Ceramic Shell for Precision Casting, *Mater. Lett.*, 2020, **276**, p 128037
49. Hu. Renzhi, X. Chen, G. Yang, S. Gong and S. Pang, Metal Transfer in Wire Feeding-Based Electron Beam 3D Printing: Modes, Dynamics, and Transition Criterion, *Int. J. Heat Mass Transf.*, 2018, **126**, p 877–887
50. G. Ahn, K.H. Min, C. Kim, J.S. Lee, D. Kang, J.Y. Won and J.H. Shim, Precise Stacking of Decellularized Extracellular Matrix Based 3D Cell-Laden Constructs by a 3D Cell Printing System Equipped with Heating Modules, *Sci. Rep.*, 2017, **7**(1), p 1–11
51. H.K. Sezer and O. Eren, FDM 3D Printing of MWCNT Re-Inforced ABS Nano-Composite Parts with Enhanced Mechanical and Electrical Properties, *J. Manuf. Process.*, 2019, **37**, p 339–347
52. Z. Li, Li. Wang and G. Ma, Mechanical Improvement of Continuous Steel Microcable Reinforced Geopolymer Composites for 3D Printing Subjected to Different Loading Conditions, *Compos. B*, 2020, **187**, p 107796
53. W. Liao, S. Zheng, S. Chen, L. Zhao, X. Huang, L. Huang and S. Kang, Surface Silanization and Grafting Reaction of Nano-Silver Loaded Zirconium Phosphate and Properties Strengthen in 3D-Printable Dental Base Composites, *J. Mech. Behav. Biomed. Mater.*, 2020, **110**, p 103864
54. N.S. Hmeidat, J.W. Kemp and B.G. Compton, High-Strength Epoxy Nanocomposites for 3D printing, *Compos. Sci. Technol.*, 2018, **160**, p 9–20
55. K.R. Ryan, M.P. Down and C.E. Banks, Future of Additive Manufacturing: Overview of 4D and 3D Printed Smart and Advanced Materials and their Applications, *Chem. Eng. J.*, 2020, **8**, p 126162
56. Y.C. Sun, Y. Wan, R. Nam, M. Chu and H.E. Naguib, 4D-Printed Hybrids with Localized Shape Memory Behaviour: Implementation in a Functionally Graded Structure, *Sci. Rep.*, 2019, **9**(1), p 1–13
57. H.W. Kang, S.J. Lee, I.K. Ko, C. Kengla, J.J. Yoo and A. Atala, A 3D Bioprinting System to Produce Human-Scale Tissue Constructs with Structural Integrity, *Nat. Biotechnol.*, 2016, **34**(3), p 312–319
58. Y.J. Tan, X. Tan, W.Y. Yeong and S.B. Tor, Hybrid Microscaffold-Based 3D Bioprinting of Multi-Cellular Constructs with High Compressive Strength: A New Biofabrication Strategy, *Sci. Rep.*, 2016, **6**(1), p 1–13
59. L. Wang, Y. Ju, H. Xie, G. Ma, L. Mao and K. He, The Mechanical and Photoelastic Properties of 3D Printable Stress-Visualized Materials, *Sci. Rep.*, 2017, **7**(1), p 1–9
60. T. Billiet, M. Vandenhaute, J. Schelfout, S. Van Vlierberghe and P. Dubrue, A review of trends and limitations in hydrogel-rapid prototyping for tissue engineering, *Biomaterials*, 2012, **33**, p 6020–6041
61. H.Y. Jeong, S.C. An, I.C. Seo, E. Lee, S. Ha, N. Kim and Y.C. Jun, 3D Printing of Twisting and Rotational Bistable Structures with Tuning Elements, *Sci. Rep.*, 2019, **9**(1), p 1–9
62. E. Monferrer, S. Martín-Vañó, A. Carretero, A. García-Lizarribar, R. Burgos-Panadero, S. Navarro and R. Noguera, A Three-Dimensional Bioprinted Model to Evaluate the Effect of Stiffness on Neuroblastoma Cell Cluster Dynamics and Behavior, *Sci. Rep.*, 2020, **10**(1), p 1–12
63. C.D. Morley, S.T. Ellison, T. Bhattacharjee, C.S. O'Bryan, Y. Zhang, K.F. Smith and T.E. Angelini, Quantitative Characterization of 3D Bioprinted Structural Elements Under Cell Generated Forces, *Nat. Commun.*, 2019, **10**(1), p 1–9
64. M.M. Wang, R.L. Flores, L. Witek, A. Torroni, A. Ibrahim, Z. Wang and P.G. Coelho, Dipyrindamole-Loaded 3D-Printed Bioceramic Scaffolds Stimulate Pediatric Bone Regeneration in Vivo Without Disruption of Craniofacial Growth Through Facial Maturity, *Sci. Rep.*, 2019, **9**(1), p 1–15
65. D.H. Ballard, K. Tappa, C.J. Boyer, U. Jammalamadaka, K. Hemmanur, J.A. Weisman and P.K. Woodard, Antibiotics in 3D-Printed Implants, Instruments and Materials: Benefits, Challenges and Future Directions, *J. Print. Med.*, 2019, **3**(2), p 83–93
66. Z. Wu, Su. Xin, Xu. Yuan, B. Kong, W. Sun and S. Mi, Bioprinting Three-Dimensional Cell-Laden Tissue Constructs with Controllable Degradation, *Sci. Rep.*, 2016, **6**(1), p 1–10
67. K. Markstedt, A. Mantas, I. Tournier, H. Martnez Avila, D. Hagg and P. Gatenholm, 3D Bioprinting Human Chondrocytes with Nanocellulose–Alginate Bioink for Cartilage Tissue Engineering Applications, *Biomacromol.*, 2015, **16**(5), p 1489–1496
68. C. Colosi, S.R. Shin, V. Manoharan, S. Massa, M. Costantini, A. Barbetta and A. Khademhosseini, Microfluidic Bioprinting of Heterogeneous 3D Tissue Constructs Using Low-Viscosity Bioink, *Adv. Mater.*, 2016, **28**(4), p 677–684
69. D.F. Duarte Campos, A. Blaesser, A. Korsten, S. Neuss, J. Jäkel, M. Vogt and H. Fischer, The Stiffness and Structure of Three-Dimensional Printed Hydrogels Direct the Differentiation of Mesenchymal Stromal Cells Toward Adipogenic and Osteogenic Lineages, *Tissue Eng. Part A*, 2015, **21**(3–4), p 740–756
70. W. Zhang, I. Ullah, L. Shi, Y. Zhang, H. Ou, J. Zhou and W. Li, Fabrication and Characterization of Porous Polycaprolactone Scaffold Via Extrusion-Based Cryogenic 3D Printing for Tissue Engineering, *Mater. Des.*, 2019, **180**, p 107946
71. S. Ji, K. Dube, J.P. Chesterman, S.L. Fung, C.-Y. Liaw, J. Kohn and M. Guvendiren, Polyester-Based Ink Platform with Tunable Bioactivity for 3D Printing of Tissue Engineering Scaffolds, *Biomater. Sci.*, 2019, **7**(2), p 560–570
72. S. Hassanajili, A. Karami-Pour, A. Oryan and T. Talaei-Khozani, Preparation and Characterization of PLA/PCL/HA Composite Scaffolds Using Indirect 3D Printing for Bone Tissue Engineering, *Mater. Sci. Eng. C*, 2019, **104**, p 109960
73. D. Gupta, A.K. Singh, A. Dravid and J. Bellare, Multiscale Porosity in Compressible Cryogenically 3D Printed Gels for Bone Tissue Engineering, *ACS Appl. Mater. Interfaces*, 2019, **11**(22), p 20437–20452
74. A. Skardal, M. Devarasetty, H.W. Kang, I. Mead, C. Bishop, T. Shupe, S.J. Lee, J. Jackson, J. Yoo, S. Soker and A. Atala, A Hydrogel Bioink Toolkit for Mimicking Native Tissue Biochemical and Mechanical Properties in Bioprinted Tissue Constructs, *Acta Biomater.*, 2015, **25**, p 24–34
75. J.S. Park, T. Kim and W.S. Kim, Conductive Cellulose Composites with Low Percolation Threshold for 3D Printed Electronics, *Sci. Rep.*, 2017, **7**(1), p 1–10
76. E.J. Parry and C.E. Banks, COVID-19: Additive Manufacturing Response in the UK, *J. Print. Med.*, 2020, **4**(3), p 167–174
77. E.T.W. Tan, J.M. Ling and S.K. Dinesh, The Feasibility of Producing Patient-Specific Acrylic Cranioplasty Implants with a Low-Cost 3D Printer, *J. Neurosurg.*, 2016, **124**, p 1531–1537
78. K. Moiduddin, S. Darwish, A. Al-Ahmari, S. ElWatidy, A. Mohammad and W. Ameen, Structural and Mechanical Characterization of Custom Design Cranial Implant Created Using Additive Manufacturing, *Electron. J. Biotechnol.*, 2017, **29**, p 22–31
79. A. Haleem, M. Javaid and A. Saxena, Additive Manufacturing Applications in Cardiology: A Review, *Heart J.*, 2018, **70**, p 433–441
80. R. Van Lith, E. Baker, H. Ware, J. Yang, A.C. Farsheed, C. Sun and G. Ameer, 3D-Printing Strong High-Resolution Antioxidant Biore-sorbable Vascular Stents, *Adv. Mater. Technol.*, 2016, **1**, p 1600138
81. M. Boffito, F.D. Meglio, P. Mozetic, S.M. Giannitelli, I. Carmagnola, C. Castaldo, D. Nurzynska, A.M. Sacco, R. Miraglia, S. Montagnani et al., Surface Functionalization of Polyurethane Scaffolds Mimicking the Myocardial Microenvironment to Support Cardiac Primitive Cells, *PLoS ONE*, 2018, **13**(7), p e0199896

82. I. Molnar and L. Morovic, Design and Manufacture of Orthopedic corset Using 3D Digitization and Additive Manufacturing, *IOP Conf. Ser. Mater. Sci. Eng.*, 2018, **448**, p 012058
83. T. Toth, R. Hudak and J. Zivcak, Dimensional Verification and Quality Control of Implants Produced by Additive Manufacturing, *Qual. Innov. Prosp.*, 2015, **19**(1), p 9–21
84. A. Vyatskikh, S. Delalande, A. Kudo, X. Zhang, C.M. Portela and J.R. Greer, Additive Manufacturing of 3D Nano-Architected Metals, *Nat. Commun.*, 2018, **9**(1), p 1–8
85. H. Yuk, B. Lu, S. Lin, K. Qu, J. Xu, J. Luo and X. Zhao, 3D Printing of Conducting Polymers, *Nat. Commun.*, 2020, **11**(1), p 1–8
86. H. Nam, H.J. Jeong, Y. Jo, J.Y. Lee, D.H. Ha, J.H. Kim and J. Jang, Multi-Layered Free-Form 3D Cell-Printed Tubular Construct with Decellularized Inner and Outer Esophageal Tissue-Derived Bioinks, *Sci. Rep.*, 2020, **10**(1), p 1–14
87. S.R. Bazaz, O. Rouhi, M.A. Raoufi, F. Ejeian, M. Asadnia, D. Jin and M.E. Warkiani, 3D Printing of Inertial Microfluidic Devices, *Sci. Rep.*, 2020, **10**(1), p 1–14
88. L. Lee, A.M. Burnett, J.G. Panos, P. Paudel, D. Keys, H.M. Ansari and M. Yu, 3-D Printed Spectacles: Potential, Challenges and the Future, *Clin. Exp. Optom.*, 2020, **103**(5), p 590–596
89. M. Zastrow, 3D Printing Gets Bigger, Faster and Stronger, *Nature*, 2020, **578**, p 20–23
90. B. Keppner, W. Kahlenborn, S. Richter, T. Jetzke, A. Lessmann and M. Bovenschulte, Focus on the Future: 3D Printing Trend Report for Assessing the Environmental Impacts, *Umweltbundesamt*, 2018, **8**, p 35

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.