3D-Printing to Mitigate COVID-19 Pandemic

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3D-printing technology provided numerous contributions to the health sector during the recent Coronavirus disease 2019 (COVID-19) pandemic. Several of the 3D-printed medical devices like personal protection equipment (PPE), ventilators, specimen collectors, safety accessories, and isolation wards/chambers were printed in a short time as demands for these were rising significantly. The review discusses some of these contributions of 3D-printing that helped to protect several lives during this health emergency. By enlisting some of the significant benefits of using the 3D-printing technique during an emergency over other conventional methods, this review claims that the former opens enormous possibilities in times of serious shortage of supply and exceeding demands. This review acknowledges the collaborative approaches adopted by individuals, entrepreneurs, academicians, and companies that helped in forming a global network for delivering 3D-printed medical/non-medical components, when other supply chains were disrupted. The collaboration of the 3D-printing technology with the global health community unfolds new and significant opportunities in the future.

1. Introduction

3D-printing or additive manufacturing (AM) has gained phenomenal attention due to its scalable and rapid prototyping of 3D structures from various precursor materials. Flexibility in structural design, waste minimization, mass customization, and complex architectural manufacturing are some of the notable features of this printing technique. During the ongoing battle with the Coronavirus disease 2019 (COVID-19) pandemic, this technology offered some of the best prototypes that has turned out to be exceedingly productive.

COVID-19 is a severe acute respiratory syndrome (SARS) that was initially reported in Wuhan, China, and is rapidly spreading across the globe in no time. The impact of which is so huge that the World Health Organization (WHO) has declared it as a pandemic on 12th March, 2020. According to the WHO report, as of December 1, 2020, the number of cases reported globally is approximated to be 61.8 million. With a death rate of approximately 1.4 million, the situation remains acute even after a year, the case was first reported. Leaving people clueless in the face of this invisible foe, this crisis is affecting both global health and economy in bizarre ways. Surprisingly, people worldwide seem to have quickly adapted to the “new normal”, stimulated by the pandemic, through regular sanitization, maintaining social distance, quarantining, and using personal protective equipment (PPE) as recommended by the WHO.

The coronavirus initially affects the upper respiratory tracts leading to symptoms such as fever, dry cough, tiredness, shortness of breath, chest pain, muscle pain, hoarse voice, and diarrhea. The extent of being infected by this virus is completely dependent on the immune system of individuals. As per the available data, senior citizens, and people with multiple disease syndromes are more susceptible to COVID-19. The mode of transmission can be either direct via aerosols, droplets of an infected individual, or indirect physical contact such as contaminated surfaces. Airborne transmission of virus is found to be contagious like the droplet transmission, and the former has a longer lifespan in air.

COVID-19 is enlisted among the deadliest of diseases to have affected human life in the recent past, along with others like smallpox, flu, plague, AIDS, H1N1, etc. The health emergency due to the non-availability of vaccines initially, in the case of the former had made the time more trying for the scientific community around the world. Researchers are focusing on the behavioral patterns of this virus with time as it shows continuous genetic mutation. At present, scientists in top universities, institutes, and labs are working towards enhancing the mass distribution of clinically approved vaccines. In the prevailing situation, lockdowns, self-isolation, and seeking the help of public health officials are the primary measures adopted to curb the spread of the virus, globally. Those infected are being shifted to hospitals only if the situation worsens or due to the non-availability of isolation facilities.

Also, a sudden outbreak of the COVID-19 has led to an exponential increase in the number of people infected, leaving the global health care systems in deep stress. Time constraints...
and unanticipated lockdowns has further resulted in the shortage of medical supplies and disruptions in the manufacturing and supply chain. The inadequacy of medical equipment such as PPE which includes masks, face shields, goggles, etc., and clinical care facilities such as ventilators and respirators has made the situation more challenging.[31–34] The increasing demand for medical staff and health workers is further magnifying the challenges, especially when, countries are still facing a severe shortage of medical equipment to support these health workers who have to attend to this situation 24 × 7.[35–37]

It is at this critical point, that the dependence on faster and efficient technologies, to meet the demands of the medical community, escalates. 3D-printing technology proved to be of enormous help by quickly responding to this unparalleled crisis by printing PPEs, medical devices, personal accessories, and also isolation wards.[6,38,39] Several research institutes, universities, companies, 3D-printing farms, and individuals working with 3D-printing technology came forward in fighting this pandemic by using their creative skills and also by collaborating with other sectors, to print medical equipment for hospitals and health workers.[40–44] The printable components were designed using software and printed directly from STL files which are easily accessible through websites or specific community sites. This method proved to be time-saving and at the same time ensures uniformity in the 3D-printed structures.[1,3,43,45]

In short, during the pandemic, 3D-printing has stood by the global community in overcoming the unexpected shortage of protective equipment. This review focuses on most of the contributions of the 3D-printing technology towards the health sector in the wake of this deadly pandemic. It includes discussions related to various 3D-printing techniques, prototypes for medical appliances, detailed analysis of printed parts, safety regulations, and certain shortcomings associated with this technique. We have incorporated the details on how 3D-printing techniques efficiently handled the pandemic over other conventional methods of printing. In short, the article examines how helpful 3D-printing technique can be in similar cases of emergency in the future as well.

2. 3D-Printing Overview

The idea of 3D-printing emerged in 1980’s and thereafter, turned out to be revolutionary by printing objects and components that find applications in numerous fields.[4,46–48] This bottom-up approach offers a single step digitally controlled process of fabricating 3D structure in a layer-by-layer manner. The additive manufacturing (AM) technique is more user friendly due to its rapid production capacity, low waste generation, high accuracy, reproducibility, easy customization of shape and geometry, high durability, and usage of a wide range of printable materials, making this technique unique from others.[1–3]

Initially, a 3D structure is designed using a computer-aided design (CAD) software, or by 3D-scanner or by photogrammetry (a combination of images from different positions).[1,49] Successful designing is followed by conversion into a stereolithography file format (STL). The STL files undergo a slicing process and are converted to a G-code file that contains geometrical information about the structure as shown in Figure 1. In the final step, the printer starts printing 2D layers on top of each other to make a 3D structure as dictated by the G-code file.

3D-printing has been contributing phenomenally towards industry, academia, and is of relevance to various fields[47,50–54] and recently in handling pandemic.[5,6,39,55] Different types of printing techniques are available based on the printable material (metals, thermoplastics, carbon-based composites, ceramics), the complexity of printed structure, cost-effective approach, and targeted applications.[3]

2.1. Fused Deposition Modeling or Fused Filament Modeling

This approach, uses thermoplastic filaments that are melted/ extruded, down the nozzle in a layer by layer stacked manner as shown in Figure 2A. The functional active materials include thermoplastics such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyamide, etc.

![Figure 1. Steps involved in the 3D-printing of a desired object. Reproduced with permission.[1] Copyright 2016, Royal Society of Chemistry.](image-url)
This technique is widely adopted due to its relative simplicity in printing and also because of the low cost of polymers. Copper-based filaments are also used for printing, which exhibits antiviral and antibacterial properties. A discussion on these 3D-printed copper components and as coatings has been carried out in a few sections that follow (Sections 3.1, 3.5).

2.2. Vat Photopolymerisation

The rise of 3D-printing started with photopolymerization where it uses specific light sources to create 3D structures via selective curing of liquid photopolymer (resin). Stereolithography (SLA) uses UV light to focus on a thin film of photopolymer resin to solidify it to a 3D-printed structure[3,60] (Figure 2B). Digital light processing (DLP) also follows a similar pattern like SLA but uses a digital light source.[61]

2.3. Selective Laser Sintering

This method uses a powdery material (either nylon or polyamide) which is melted by thermal energy or laser heat source, into layers of a solid structure as shown in Figure 2C. The main advantage of selective laser sintering is that it doesn’t require any external support, hence it can easily produce designs, with complex geometries.[1,47]

2.4. Polyjet Technology

It is an alternative photocuring technique, where it uses inject methods to deposit photocurable multi-material structures as designed in layers and is followed by hardening these layer using UV light (Figure 2D). High-resolution flexible materials are printed mainly focused on fluidic devices.[1]

2.5. Multi Jet Fusion Technology

This is a printing technology that prints, by evenly heating a powder bed. Since this method does not use laser-based materials, it can print components with smooth surfaces, high density, and low porosity. This method produces functional parts which require limited finishing. The jetting of the fusing agent in portions where there has to be selectively molten particles, and jetting a detailing agent along the outline, improves the resolution of parts. When an energy source (a lamp in this case), is passed over the powder bed, the jetted materials capture the heat and distribute them within the system. This method has proved to have an upper hand over injection molding at multiple levels.
because of being cost-effective and producing prototypes with better mechanical properties.\[62\]

3. 3D-Printed Medical and Safety Devices

In the previous section, we have come across various 3D-printing techniques that are essential to device medical and hand-free safety tools. In this section, we shall discuss how the digital printing world with the rapid prototyping ability of the tech community has been benefiting the health and scientific community in limiting the spread of the virus at a significant level. The 3D-printing of medical and safety devices extends from PPE to specimen collectors, isolation wards, and personal accessories printed by various enterprises.

3.1. Personal Protective Equipment

PPE helps to limit the spread of infection by protecting the user from airborne liquid contaminants/particles. It acts as a barrier between a healthy and an infected person. PPE includes face shields, facemasks, goggles, etc. The items are need-based and situational and therefore, find different purposes among individuals, health workers, and medical staff.

3.1.1. Face Shield (Class I)

The shortage of face shields was one of the critical challenges faced by medical staff especially during the interactions with patients. This protective equipment helps the user, by safeguarding their eyes and mouth from infectious airborne particles, droplets, splashes, and body fluids.\[63,64\] The face shields are printed using FDM, due to its simple geometry and improved choice of printable materials.\[65\] These 3D-printed frames contain a reusable headpiece and a plastic sheet attached to the frame that acts as a protective shield. Recently, Prusa, a well-known FDM manufacturer in the Czech Republic had 3D-printed nearly 200 000 face shields (Figure 3A) and donated them to medical practitioners and other professionals.\[66\] Also, during the pandemic, the engineering department of airlines companies like Etihad collaborated with their own medical wing to make 3D-printed face shields, using recyclable plastic, designed via SLS method, and supplied it to hospitals across UAE.\[67\] Celik et al.,\[68\] proposed designs of face shields that are lighter, simple to use, relatively more ergonomic, and avoids unnecessary components such as elastic bands, clips, etc. Each frame weighed < 10 g and was printed in a short time and showed remarkable productivity. A Canada based company called Next Generation Manufacturing Canada (NGen) invested more than $21 million in manufacturing companies to produce face shields, ventilators, and test kits in a limited time frame.\[69\]

3.1.2. Facemasks

Both N95 (class II by FDA) and surgical masks are used for protection against viruses and bacteria but differ in their filtration efficiency.\[73–75\] The efficiency of a 3D-printed mask is strictly correlated to its printing quality, facial anatomy, filters used, fitting, etc. 3D-printed N95 replacement masks with silicone cast masks that seal around the face of the user was proposed by Barrow neurological institute, (USA).\[76\] By making use of a 3M P100 filter, this model exhibits a high filtration rate and with an efficiency that can last up to three months. Replacing defective or broken bands by 3D-printed frames ensured a longer lifetime of masks in the case of both N95 and KN95 masks and also proved to be a better fit for the user.\[77\] CERN, the European Organization for Nuclear Research, followed all the regulatory and safety specifications similar to the surgical type I mask, to design 3D-printed flexible and washable masks with replaceable filters.\[78\] They also developed an alternative for 3D printers that lacks the capacity of printing flexible items, by separately printing a mould injected with silicon in a rigid plastic material. 3D-printed stopgap face masks are exclusively designed as a substitute to standard PPE, used only in cases of emergency or shortage.\[79\] These masks are 3D-printed using MJF, SLS using powder-bed nylon, or SLA using BioMed Clear.\[80\] Similar 3D-printing projects were also carried out to make 3D-printable masks, such as the Montana Mask and the Lowell makes mask. Montana mask is known for its high and effective filtration capacity and can also be easily printed on desktop machines.\[81\] They can also be sanitized after each use. Lowell makes mask,

Figure 3. 3D-printed A) face shields from Prusa, Reproduced with permission.\[66\] Copyright 2021, Prusa Research a.s. B) Face masks from HEPA, Reproduced with permission.\[70\] Copyright 2020, Tovarna.Tech.
being an alternative form of replaceable front filter designs, provides better and easy printing options with no support or adhesion.[82,83] Health workers are suggested to use full face snorkel masks connected using 3D-printed adaptor valves.[84,85] The use of a High-Efficiency Particulate Air (HEPA) filter makes this mask promising as well. However, conflicting results were obtained in the efficiency of snorkel (HEPA) filter makes this mask promising as well. However, conflicting results were obtained in the efficiency of snorkel masks in comparison to N95 respirators making their usage debatable and subjecting them to undergo further quality tests.[86] The use of PLA filaments as active materials to design HEPA masks (Figure 3B) was found to be interesting due to its replaceable filter port and better fitting, for both male and female users.[87] However, the fragile nature of PLA can harm the facial skin of the users in the case of an accident. Things like user iczfirz, suggested a remedy by printing it on cloth, making it more flexible and comfortable.[88] Another notable method adopted for manufacturing 3D-printed masks was carried out using copper. Copper, known for its antimicrobial and antiviral properties in traditional as well as scientific societies has always found numerous applications in the field of biomedicine.[89,90] Studies suggest that copper, on reaction with oxygen, generates a reactive free radical that can effectively fight the virus.[91] Understanding the potentials of this metal, researchers and companies have made ample use of it in designing masks to fight the pandemic.[92] Copper 3D, a well-known US-based company has addressed the shortage of N95 masks using PLACTIVE and MDflex by FDM/FFF printing.[93] These printed masks known as NanoHack exhibited antiviral properties. Moreover, the same was modular, reusable, washable, recyclable, and cost-effective. To achieve the above mentioned target in minimum time, companies and other enterprises collaborated to manufacture 3D-printed copper masks.[94] An enterprise called Creality (China) also developed 3D-printed face masks, and 3D-printed face mask buckles which gives comfort and relief from pain in the ear of user.[95] They also donated a significant amount of their products to various hospitals.

3.1.3. Personalized 3D-Printed Masks

The severity of the pandemic has forced government agencies to ensure that their citizens wear masks. The uneasiness of adapting to this new accessory has caused several discomforts to the users and the gaps arising due to poor fitting of masks increases the chances of being infected. These discomforts also stem from the diversity of the facial anatomy of the users which differs from person to person. 3D-printed structures expect to bring a systematic resolution to these inadequacies with the use of 3D facial scanning software that can improve the fitting of the mask.[96] Personalized 3D printed face mask fitters were hence designed to improve the fit of the surgical masks, preventing fogging and better sealing. These mask fitters are customizable using a face app, developed by Bellus3D,[97] capable of capturing a 3D scan of the user’s face to produce a 3D mask design file, which can subsequently be 3D printed. Imperial College London (UK) has also proposed ideas for creating customized face masks.[98]

3.1.4. Protective Eyewear

Safety goggles are used for sealing the eyes and giving them protection from the droplets of an infected individual. Boltian, a Spanish designer, designed protective goggles with 3D-printed frames.[99] The lens of this goggle was made using PVC or PC of 1 mm thickness. PVC can be cut easily, due to its flexible nature, either manually or by using a laser machine. Huaxiang, a Chinese company sketched a 3D design and printed it on the Farsoon 430P system. Sealing rings were made from LEHVOSS and transparent acrylic was used for lenses with an anti-fogging coating.[100] 3D-printed protective goggles were of huge help for hospitals in Wuhan, China, during massive shortage.[101]

3.2. 3D-Printed Medical Accessories

Mechanical ventilators are an essential secondary component that support patients experiencing difficulty in breathing. During the pandemic, even automobile companies such as Volkswagen manufactured 3D-printed ventilators which had benefited the concerned sectors.[102] Patients experiencing severe respiratory problems are incubated and treated in invasive mechanical ventilation (IMV) procedure.[103,104] Unfortunately, this procedure involves risking the patient’s health (overdose of sedatives) and that of the health workers (risk of contamination) during intubation.[105,106] Hence, per the recommendations of the WHO, patients are primarily subjected to a non-invasive ventilation (NIV) procedure such as continuous positive airways pressure (CPAP), which comparatively involves less risk.[107] HEPA filters, regarded as an improved safety measure, assist in the filtration of exhaled air after NIV. 3D-printed emergency valves such as ventilator valves are also among the key components that are being used during the pandemic to support a patient’s breathing. Required concentrations of oxygen are given to patients via ventilator valves, connected to the patient’s face mask.[108,109,110] At a time when the demand for 3D-printed valves for respirators was and is still on raise, in many parts of the world, a prompt action taken by an Italian engineering startup called Isinnova (Italy) proved to be life-saving. Isinnova 3D-printed what is called a venturi valve (Figure 4A), through reverse-engineering a design of the official part.[108,109] Though

Figure 4. A) 3D-printed venturi respirator valves by Italian company. Reproduced with permission[108] Copyright 2020, ISINNOVA S.R.L. B) Snorkeling EasyBreath masks connected to Charlotte Valves. Reproduced with permission[109] Copyright 2020, ISINNOVA S.R.L.
this method was of huge help to multiple hospitals in Italy, this prototype could not be widely distributed or used, due to quality concerns and copyright issues.

3D-printed connector valves named Charlotte Valves were designed by Isinnova, an Italian engineering company. Isinnova enhanced the Easybreath snorkeling mask from Decathlon using the Charlotte Valves, that when connected to an oxygen supply, performed like a functional ventilator (Figure 4B). In case a reservoir is required, this model can also be equipped with a 3D-printed Dave valve. This approach was found to be a success, and attracted several companies, leading to a massive production via various printing techniques such as FFM, SLS, and SLA. Rosatom (Russia) also 3D-printed venturi valves which combined with aerosol masks, enabling the flow of oxygen at a low rate.

3.2.1. Splitter

The sudden increase in the number of COVID patients during the pandemic caused a severe shortage of medical equipment such as ventilators as discussed in the above Section. 3D-printed splitters were of huge benefit in these circumstances since they could be used to supply oxygen to multiple patients at the same time using a single ventilator. Ayyıldız et al. 3D-printed two-port and four-port splitters using a 3D-printer with polyjet technology. Several experiments were carried out and it was concluded that two port splitters were more efficient for supplying airways using a single ventilator to more than one patient. In short, 3D-printed splitters were found to be an alternative to mechanical ventilators. While there are still concerns about the possible risks involved in using 3D splitters, several institutes, like Johns Hopkins University (USA), Prisma Health (a health organization in South Carolina, USA) and others have come up with innovative 3D-printed splitters that can be shared among multiple users. Some of which assure “free use”, giving access to people across the world to print these designs and contribute to those concerned.

3.3. 3D-Printed Specimen Collectors

Test kits for COVID-19 is yet another significant medical apparatus that was widely used for confirmation of infection during the pandemic. The diagnosis is usually done using, either polymerize chain reaction (PCR) or antibody testing. Nasal secretions from the nose and throat are collected by the nasopharyngeal (NP) swabs and oropharyngeal swabs. The former method was widely adopted and is a sensitive technique of virus detection in individuals. During the initial days of the outbreak, there was a shortage of swabs, but in no time, this emergency was resolved using a novel 3D-printed swab. The University of South Florida’s (USF), health collaborated (USA) with the Northwell Health to design 3D-printed alternative swabs via SLA as shown in Figure 5A,B. These 3D-printed swabs are convenient tools that can strengthen the efficiency of sample collection, since they come up with complex tip structures, unlike swabs with flocks at the tips. They exhibit efficient flexibility, are sterilizable, durable, and are user friendly as they can be inserted and removed easily by the medical professionals. EnvisionTEC engineers (Germany) designed a 3D printed collection tip for a flexible nasal swab which was 3D-printed in bulk, (hundreds of swabs in a single batch) and was rinsed in isopropanol, followed by dehydration for 30 min. The cooled swabs are irradiated with UV light and processed to check their quality to meet the required specifications. Finally, they are certified, sterilized, and dispatched to various health care units.

FDM of polyethylene terephthalate glycol (PETG) filament using Prusa MK3s printer was carried out by Cox and Koepsell to fabricate 3D-printed swabs of 15 cm length and 600 mg weight. They were clinically tested and were found to be similar to commercial swabs in performance. Another group, 3D-printed swabs with a domed tip possessing an open lattice design using direct light projection. This showed that the 3D-printed swab with locally designed specifications was found to have a sensitivity and specificity of 89% and 92%, respectively. Also, 90% of the results obtained using 3D-printed swabs were found to be matching in comparison to the commercial one. Several companies came forward to 3D-print these swabs and extended their support to the medical community. Formlabs (USA) 3D-printed swabs for PCR testing to support the medical crew in a US hospital and also shared their files with hospitals outside the USA. A well-known company Carbon (USA) quickly responded to the situation by designing and producing patient sampling swabs. In short, 3D-printed nasopharyngeal swabs provide a cost-efficient and fast alternative to the standard NP swabs used for the COVID-19.

3.4. Isolation Chambers and Emergency Dwellings

Isolation of infected individuals and those under quarantine is a mandatory COVID protocol directed by the WHO. However, the lack of facilities in the hospitals to isolate huge numbers of patients and individuals under observation increased the demand for an alternative solution. 3D printing of transitory dwellings to quarantine individuals was of huge advantage in these tough times. Since 3D-printed mobile wards require a shorter construction time, making this method more favorable for those in need.
Cubillos et al. \cite{124} designed a cubical frame using PVC pipes and enveloped it with a plastic bag as shown in Figure 6A. Suction/vacuum mechanism was used inside the system to create a negative air flow isolation chamber, preventing the air outside the chamber from getting contaminated. Equipment was hanged inside the chamber on 3D-printed hooks and multiple ports were assigned for suction, oxygen delivery, and nebulization. A similar effort was done at the Texas A&M University (USA) \cite{125} (Figure 6B), where 20 isolation chambers were designed to prevent the breath of incubated people from getting released to the surroundings. Since, virus transmission can also occur from the stool of infected individuals, 3D-printed isolation wards are also equipped with environmental friendly toilets (Figure 6C). \cite{126} This method, therefore, ensures hygienic living during the isolation period. 3D-printed mobile homes, similar to isolation wards were printed in 2 hours (h) using concrete and recycled materials where each structure had an area of 10 m² and 2.8 m height. Reports also showed that the company printed nearly 200 wards (Figure. 6D) to house medical staff. Being mobile, these houses can be easily transported and electrified as per convenience. \cite{127} WinSun/Yingchuang (China) transported nearly fifteen 3D-printed isolation wards to Pakistan to fight the pandemic. \cite{128}

3.5. Hand Free Accessories and Antimicrobial Tools

The life-span of the COVID-19 virus differs significantly on various surfaces with an average stay of nearly 72 h. They sustain for \( \approx 3 \text{ h} \) in the airborne droplets, 24 h on cardboard, and for a longer duration of up to 72 h over stainless steel and plastics. \cite{129-132} High risk for contamination from the above situation through indirect contact at public places call for solutions that can reduce the risks. 3D-printed hand-free tools work towards achieving this goal. To prevent direct contact with contaminated surfaces, Materialise (Belgium) 3D-printed door openers that can be opened using the elbow (Figure 7A) and button-pushers (Figure 7B). \cite{133} François et al., have also developed hand-free door openers, door hooks, and button-pushers to prevent contamination. \cite{134} Innovative inputs like, 3D-printed wrist band, to attach sanitizer was designed by an engineer from Saudi Arabia. The device, printed using the FDM approach, contains antiseptic gel attached to the wrist that can lather up the palms of the user without holding the bottle. \cite{135}

Copper nanoparticles as coating over fabrics, cotton, polymers, etc. are commonly seen and are found to be effective in hindering the attacks of viruses like SARS CoV. \cite{136} Copper is predominantly used as a coating material rather than being employed as a bulk material. This is due to the fact that the direct 3D-printing of copper is tedious due to the high conductivity of copper which results in thermal issues. \cite{137} A similar approach was adopted where cold spraying technique was used to coat copper over steel parts to eradicate the virus from these surfaces. \cite{138} The ability of copper in fighting viruses and bacteria are evident from the above examples and it is anticipated that their use shall lead to highly improved mechanisms that can limit contamination from viruses similar to COVID-19.
Doremalen, in his studies, showed that the stability of the virus over copper is limited to 4 h. Therefore, the antimicrobial property of copper was used as a preventive measure against COVID-19 virus. A similar idea of using copper foils to coat doorknobs and the elevator buttons of buildings was carried out by the Ministry of Science and Technology of Taiwan.

3.6. 3D-Printed Respiratory Swabs Simulators (Medical Manikin) and Visualization Aid

The pressing demand for trained staff to collect swabs during the pandemic was yet another critical situation that sought urgent attention. Since the number of individuals infected was huge, governments had to take the help of even non-professionals and train them to collect swabs, to increase the rate of testing. As can be understood, this requires a massive and effective task force, primarily for training individuals. 3D-printed respiratory swabs simulators or bio models were of immediate help in these worrying times as shown in Figure 8A–D.

To aid healthcare workers to perform swab testing, transparent 3D-printed respiratory swabs simulators that projected the internal structures were provided to the trainees for performing trials. This ensured that these trained workers would work efficiently while collecting the samples without causing discomfort to those being tested. Visual and tactile education models were 3D-printed to educate visually challenged individuals for getting a better understanding of various structures.

3.7. Data Sharing and Contributors

CAD, STL files related to 3D-printing medical accessories are readily shared with users in specific websites, social media, or at file repositories, saving a lot of time for the user in designing. Several institutes/community came

Figure 7. 3D-printed A) door opener B) button pushers from Materialise to prevent contact from a contaminated surface. Reproduced with permission. Copyright 2021, Materialise.

Figure 8. A–D) 3D-printed respiratory swabs simulators for swab collection from Creatz3D and Aumed (Singapore). Reproduced with permission. Copyright 2021, AuMed.
forward to print 3D-medical components to fight the pandemic of which few are listed as:

1) Print farms in USA, Europe, and China has contributed to printing during the pandemic to address the needs of the masses. Barcelona-based BCN3D (Spain) contributed their 63 in-house print farm to fight the pandemic. Airwolf3D (USA) contributed towards pandemic by printing face shield, valves and other medical components.

2) Universities such as the University of Washington (USA), Case Western Reserve University (USA), University of Tennessee (USA), Swansea University (UK), University of Hull (UK), Czech Technical University (Czech Republic), Brno University of Technology (Czech Republic), Michigan State University (USA), and Penn State University (USA) are a few to list.

3) Industries and Companies like Formlabs (USA, Spain), Carbon (USA), Desktop Metal (USA), 3D Systems (Australia, Belgium, China, France, Italy, Netherlands, UK, USA), Stratasys (US, Israel), Johnson and Johnson (Ireland, Switzerland, UK, China & USA), HP Inc. (Spain, US, Japan, and Europe), Markforged (USA) are leading the way with their machines and materials.

Many notable designs were also found from repository files such as NIH 3D Print Exchange, Grab CAD, Thingiverse and projects from Creality, Prusa, Isinnova, Materialise etc.

3.8. Regulatory Bodies

Though several countries have softened their safety and regulatory laws regarding medical devices due to the continuing medical emergency, the welfare and safety of individuals cannot be negotiated. Thus, designers and manufacturers of 3D-printing devices must maintain the safety regulations, dictated by various governmental bodies as they are still not waived off completely. Designers must use approved materials and ensure the basic quality of the materials used, based on the international risk classification system. This includes documentation of pre and post-manufacturing processes, running through ISO 13485-compliant quality-management system, and an internationally standardized biocompatibility check. Complying to these regulatory guidelines, guarantees trust among users of 3D-printed medical devices. Other than these procedures of approval and certifications, concerned agencies must rectify issues of copyright violations. As confusions at these levels between various players of the market lead to slowing down of responses to the urgency and can risk lives. Therefore, manufacturers of 3D-printed medical devices must synchronize their production work with concerned sectors for accountability, quality, and safety assurance.

3.9. More 3D-Printed Devices

Table 1 represents various 3D-printed components printed during the pandemic to support the global shortage of supply.

3.10. 3D-Printing Versus Conventional Methods in COVID Times

The 3D-printing industry proved to be an efficient counter-part to the conventional methods of manufacturing during the COVID-19 pandemic. More than a question of contestation, 3D-printing sought only to enhance or parallelly co-exist with the existing printing techniques, in most cases during the emergency. Both 3D-printing and traditional techniques were employed to tackle the pandemic. Having said that, this does not minimize the advantages that 3D-printing has over other conventional modes of printing, especially in cases of emergency. By producing health-care accessories in minimum time and reduced cost, this method proved to be beneficial at several levels. Traditional manufacturing (subtractive manufacturing) involves carving the desired structure out of a bulk material. The end product obtained is cut down into several parts and are later put together. The excess waste generated during manufacturing, and the high complexity associated with the products, makes this technique highly expensive and limits its usage especially during times of emergency. Kunkel et al. put forth a comparative study between the two

### Table 1

| 3D-Printed parts and their components | FDM | SLA | SLS | MJF | Polyjet |
|-------------------------------------|-----|-----|-----|-----|---------|
| Face shield                         | [66,165–168] | [154,168–171] | [154,172,173] | [157,174–176] |         |
| Facemasks                           | [152,177–181] | [80] | [80,174,182] | [183] |         |
| Facemask straps and fitter          | [94,165,184–186] | [187] | [174] |         |         |
| Respirator (N-95 or similar)        | [42,84,188,189] | [190] | [191] |         |         |
| Safety goggles                      | [97] | [97] | [97,192] |         |         |
| Valves / Ventilator                 | [193,194] | [194,193] | [154,196,197] | [5] |         |
| Nasopharyngeal swabs                | [119,198,199] | [199,200] | [201] | [202,203] |         |
| Hand-free tools                     | [134,160,204,205] | [160] | [160,174] | [134] |         |
| Camera mounts                       | [206] |         |         |         |         |
techniques which suggests that while conventional methods of manufacturing, like injection molding, were able to produce a large number of products through a centralized mechanism, the initiation of process took more time and was expensive. Further, the products made could not be quickly accessed by hospitals due to the disruption in supply chain because of the pandemic. A major setback to the traditional manufacturing industry was felt due to the shutting down of factories and shortage of laborers during the pandemic and the lockdown that followed. 3D-printing, on the other hand, was quicker in manufacturing emergency medical equipment, such as the PPE, ventilators, test kits, emergency dwellings, medical accessories, etc. through rapid prototyping, from multiple locations, at a cheaper rate during COVID-19.[6,165,211] The time required for delivering these 3D-printed products was also lesser, since 3D-printing services functioned as a network where individuals, institutions, and companies usually collaborated in aiding the health sector and ensured faster delivery. A significant service was done using 3D-printed drones that helped in delivering medical equipment swiftly during the COVID-19 pandemic.[212] Another study also observed that a combination of both the methods (3D-printing and injection molding), especially reduces the cost and enhances the production speed of printing.[80,213,214]

Other findings also note that 3D-printing reduces the shipping and manufacturing costs and around 70% of prototyping costs involved in traditional manufacturing.[215] The digitally-enabled mechanisms of 3D printing techniques cut shorts a number of these processes, and thereby can be accessed at a cheap rate from any part of the world.[165,216] Generally, the cost involved in the updation of the product remains the same in case of 3D-printing at all stages, and also the product can be improved multiple times before its mass production at the initial cost itself. At a time of ample shortage and rising demands like the pandemic, conventional methods fail to deliver an immediate response, since, repeating the process of manufacturing takes more time via this method.[211] Also, a minor change in one of the parts can affect the whole design, in the case of conventional methods. The method, therefore, does not look ideal in case of an emergency. The cost of complexity is lesser in the case of 3D-printing since it creates a finished product in a single step, aborting the assembling process involved in conventional printing which reduces the labor cost and time as well. The speed of manufacturing the finished products is faster in comparison to the traditional manufacturing as well.[215] Hence, 3D-printing technology proves to be highly advantageous in order to handle exigencies like the current pandemic. Further advancements in this field can therefore, offer quality results in the future.

4. Limitations

Though 3D-printing of medical devices played a vital role in handling this health emergency, like any other technological innovation, this method also has certain flip sides that has to be addressed for future advancements. One of the drawbacks is the evasion of prime concerns like safety and legal precautions due to the rapid 3D-printing of medical devices to meet the urgent requirements during the pandemic. Since these devices are primarily used for medical purposes, safety of these printed equipment must be ensured.[165-163,217] Also, due to the same reason of being rapidly produced, manufacturers tend to show negligence towards biocompatibility and sterilizability of these printed medical devices. Since all this equipment is of long term use, it is important to have them clinically approved because even a small piece of defective equipment can harm the life of a medicated person.[215,218,219] As getting, sanitizing and medical clearance from concerned authorities involves several formalities, hospitals are compelled to use unlicensed medical equipment from companies, due to the time constraints, during the emergency. At the same time, unlicensed products, randomly distributed at hospitals by the companies, can also get rejected due to lack of safety information about the printed medical equipment. This results in a wastage of time and resources, at the manufacturer’s end. Hence, the concerned agencies must consider these things before the mass production of 3D-printed medical devices.[220]

Getting a legal sanction of printed materials, processing and clinical testing takes a lot of time and is expensive.[64] Since the demand for medical equipment during the COVID-19 pandemic was huge, the delay in approval from concerned authorities was another significant challenge that slowed down the procedures. Legal sanctions are also tied with ethical issues, especially while testing these 3D-printed devices for human compatibility which involves consent from concerned individuals. Using non-human entities for testing, in case of urgency also involves moral concerns.[6]

3D-printing of medical devices from the same STL file may aberrate from its standard configuration due to the variations in printable material, printer, and software used by different manufacturers. The failure in reproducing uniform structures can alter the physical properties of these printed materials, creating a confusion of choice among users. This dilemma about the approved configuration, may reduce printing efficiency, wastage of manpower, resources, and may come at varying costs.[165,221] Also, poor interface and unsealed protective covers may arise during printing, minimizing the quality of protection.[2] Regulation of customized 3D-printed face masks remains a significant limitation, though it ensures better fitting than the commercially available ones. Although primarily, this technology uses certain regulatory metrics such as fitness and filtering efficiency,[222] the lack of proper fit testing for individual masks, shall increase the chances of getting affected by the virus.[223] Hence, it reduces the overall filtering efficiency of these masks. Therefore, only a stringent evaluation of each of these individual masks would ensure improved safety which has to be monitored using both quantitative and qualitative fit tests, long-term stability tests, and checking its airborne particle protection levels.[224] Also, the medical community is unaware of the living conditions of people who are printing this medical equipment. If he/she happens to be an infected individual, then there are chances that the equipment printed by him/her may get contaminated and would risk the lives of others using it.

Choice of a functional material for printing includes thermoplastic filaments, powders, ceramics, metals, and many others. However, a study showed that 3D-printing respirators using FFF and powder bed fusion method showed low filtering
efficiency towards COVID-19 virus.[225] Studies that use ceramic and metal-based active materials as 3D-printing medical components have not been undertaken yet. This might be due to the high cost involved in the 3D-printing of metals.[5]

5. Conclusions and Future Prospective

This review is an account of the multiple ways in which 3D-printing benefited the medical community during a sudden disruption in supply. The various ways in which the COVID-19 pandemic affected the general nature of life on earth is immeasurable. Perhaps, only a “post COVID world” would tell us what has changed for the global community. One of the major impacts was felt on the global health care systems itself. The methods available to control the spread of the virus were too limited initially, due to obvious reasons of COVID-19 being a health emergency. The virus’s unpredictable behavior, as it underwent repeated genetic mutation made the situation even harder for the global health communities. Since, the mass distribution of vaccines which has been recently developed, such as, Covishield (UK), Sputnik V (Russia), Moderna COVID-19 Vaccine (US), Covaxin (INDIA), CoronaVac (China), etc.,[226] is still underway, there has to be a feasible solution to reduce the death rate and methods to control the virus’ spread. Hence, the significance of 3D-printed safety equipment remains, until the full-fledged distribution is achieved. 3D-printing technology offered enormous possibilities in these difficult times that proved to be life-saving. The shortage of medical devices and other components were resolved using a wide variety of 3D-printed structures. Equipment like face shields, face-masks, goggles, swabs, isolation wards, ventilators, splitters were 3D-printed in a limited time to meet the demands of hospitals and other concerned authorities. Rapid prototyping with customized fabrication and a low amount of waste makes 3D-printing an acceptable approach to meet various demands in a short period. Addressing a few challenges related to safety and approval of materials, quality concerns, legal and ethical issues, etc. shall certainly guarantee better advancements in this sector. Meanwhile, the timely involvement of universities, labs, companies, and entrepreneurs has improved the production of 3D printed equipment.

However, concerns on whether 3D-printing technology shall effectively replace the existing modes of conventional printing is still prevailing. Perhaps, we would suggest 3D-printing method to be a parallel technology of printing rather than a replacement of conventional mass production methods such as injection molding. 3D-printing proved to be efficient in situations of emergency like the current pandemic, when the supply-chain was interrupted, and conventional methods, found difficulty in transporting the products in a limited span of time. Due to its rapid prototyping ability, quick delivery through organized networks, ease in installation and accessing the designs from the internet from any part of the world, this technology came in handy during this unprecedented emergency. This method is cost-effective in terms of materials used and labor as well. However, for large scale production in a limited amount of time, the conventional methods still have an upper hand. Perhaps, the speed at which 3D-printing is evolving, to go by the existing research, the conditions are promising. It is expected that this technology shall advance and will play a major role in industry, academics, and everyday life.

The use of bioactive material for 3D-printing is expected to open enormous possibilities in handling future pandemics as well. This is also true in the case of ceramic and metal-based active materials for 3D-printing. Studies on the use of bio-inks for bio-printing is at their initial stage now and if explored, would be a great contribution towards regenerative medicine. Thus, the COVID-19 pandemic facilitates itself to be a suitable case of recognizing collaborative approaches of 3D-printing technology for future prospects as well.

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Conflict of Interest

The authors declare no conflict of interest.

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