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Review

The Unprecedented Role of 3D Printing Technology in Fighting the Covid-19 Pandemic: A Comprehensive Review

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Abstract: The Coronavirus disease 2019 (COVID-19) rapidly spread to over 180 countries and abruptly disrupted the production rates and supply chains worldwide. Since then, 3D printing also recognized as additive manufacturing (AM) and known to be a novel technique that uses layer-by-layer deposition of material to produce the intricate 3D geometry, has been engaged in reducing the distress caused by the outbreak. During the early stages of this pandemic, shortages of Personal Protection Equipment (PPE), including facemasks, shields, respirators, and other medical gears, were significantly answered by remotely 3D printing them. Amidst the growing testing requirements, the 3D printing emerged as a potential and fast solution manufacturing process to meet the production needs due to its flexibility, reliability, and rapid response capabilities. In the recent past, some of the other medical applications that have gained prominence in the scientific community include 3D printed ventilator splitters, device components, and patient-specific products. Regarding the non-medical applications, researchers have successfully developed contact-free devices to address the sanitary crisis in public places. This work aims to systematically review the applications of 3D printing or AM techniques that have been involved in producing various critical products essential to limit this deadly pandemic's progression.

Keywords: COVID-19; 3D Printing; Additive Manufacturing; Medical Applications; Open-source files; Innovation.

1. Introduction

COVID-19 is an infectious disease caused by a lately discovered coronavirus named Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) [1]. Most COVID-19 infected people will experience mild to moderate respiratory illness and can recover without any special medical treatment. Those with pre-medical histories such as diabetes, cancer, cardiovascular and chronic respiratory diseases are more likely to develop severe illness [1]. Almost every aspect of human life has been affected by COVID-19 pandemic [2]. As on 31 July 2022, more than 574 million people have been infected by the COVID-19, and 6.3 million deaths have been reported globally [3]. It has been well documented that the very first few cases of the COVID-19 were reported in Wuhan, China, as early as

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December 2019 [4-6]. Since then, the novel Coronavirus has spread to over 180 countries [5]. The World Health Organization (WHO), on Mar 11, 2020, declared the COVID-19 as a pandemic [7].

During the early months of the first outbreak, most countries were forced to be under lockdowns to prevent the further outbreaks [8]. This led to an unprecedented situation in which even the best of the manufacturing industries started failing to produce and dispatch modest protective gears to limit the spread of the virus [8]. Trade and transport restrictions, border controls, production disruptions, and quarantines have greatly affected the global supply chain of critical medical needs [9]. A study has stated that about 35% of the supply chains has already been disrupted, and 53% of the manufacturers have anticipated the change in operations due to COVID-19 [10]. According to the director-general of WHO Dr. Tedros Adhanom Ghebreyesus, "Without secure supply chains, the risk to healthcare workers around the world is real. Industry and governments must act quickly to boost supply, ease export restrictions and put measures in place to stop speculation and hoarding. We can't stop COVID-19 without protecting health workers first" [10]. Ever since the advent of this unprecedented situation due to the COVID-19 pandemic, the world has been seeking rapid solutions to meet life-saving medical requirements. An optimal assistance from the emerging technologies including internet of things, additive manufacturing, cloud computing, artificial intelligence, big data, blockchain, and 5G, was immediately required to effectively improve the collective global efforts in virus tracking, prevention and control, epidemic monitoring, treatment, resource allocation, and vaccine development [8].

Unlike subtractive manufacturing, AM is a layer-wise material addition process where a layer of material will be deposited over a previously deposited layer. AM/3D printing technology has emerged as an alternative and rapid solution to manufacture PPEs and medical devices [11]. This review article aims to provide an insight into the role of AM/3D printing technology as a lifeguarding technology to combat the unprecedented situation of the COVID-19 pandemic. The report also includes information on how this desktop technology with the digital interface responded rapidly to tackle the Coronavirus challenges domestically when the big manufacturing firms closed their doors considering the health risks associated with their mobilized workforce.

2. Methodology

Initially, many research articles, short notes, announcements, letters, and other related data from the internet sources were collected. A detailed literature survey was conducted using Scopus, PubMed, and Google Scholar database with keywords "COVID-19 and additive manufacturing", "Coronavirus and additive manufacturing", "technology and COVID-19", "COVID-19 and 3D printing", "Coronavirus and 3D printing", "3D printing PPE", and "3D printed isolation wards". Next, the collected database was scrutinized to organize it into three sections, namely 3D printing in medical application, 3D printing in the non-medical application, and 3D printing in construction of isolation wards. Finally, the irrelevant articles and data were ignored from the database, retaining the related ones. All these associated articles and internet source data were combined in a resourceful manner to provide insight into the role played by 3D printing/AM to fight against the novel Coronavirus. A detailed workflow chart of the methodology followed is as shown in Figure 1.

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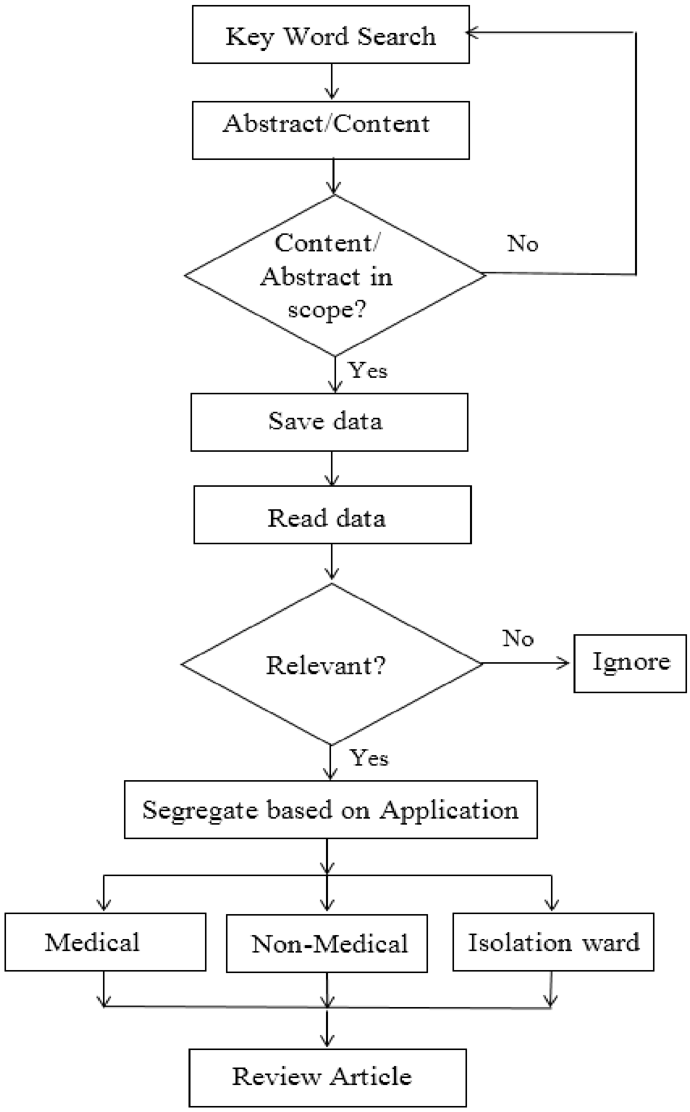

Figure 1. Detailed flow chart of the methodology followed.

3. 3D Printing and COVID-19

3D printing/AM is a prominent technology that can provide rapid solutions in its fields of application. The significant AM features include rapid response, remote manufacturing, flexibility, decentralized manufacturing, and customization [12,13]. The decentralized manufacturing nature of 3D printing can bring out the local microgrids of 3D printing-based manufacturing firms leading to on-demand manufacturing [14]. These microgrids can supply critical parts locally during severely disrupted supply chains [13]. Also, AM offers minimum assembly and post-processing steps to deliver the finished products without a need for a mature supply chain and extensive logistics [15]. AM currently features the minimum possible time between thought to product. Flexibility and desktop manufacturing capabilities associated with 3D printing technology have answered the problems arising from global supply chain disruptions. Figure 2 illuminates the application areas of 3D printing during the COVID-19 pandemic.

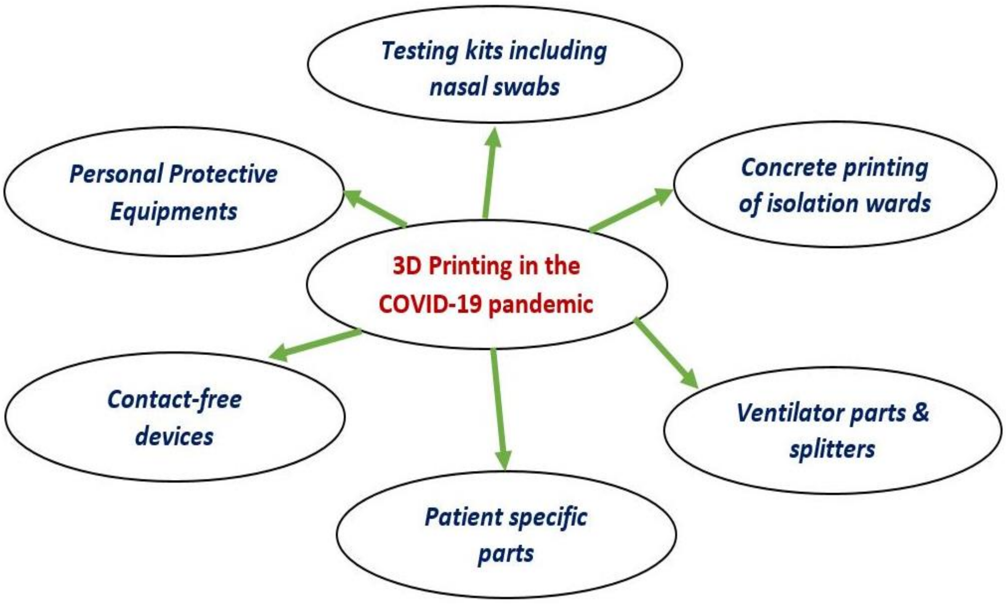

Figure 2. Wide range of applications of 3D printing during the COVID-19 pandemic.

The era of AM started with limited practical values including prototyping. Nevertheless, it has outgrown to a mainstream manufacturing technique with wide acceptance in numerous prominent industries, including automotive, aerospace, defense, and healthcare. In the last decade, the evolution of technology for the medical applications has followed the paths of both imagination and problem-solving [16]. Digital technologies like cloud and digital communication channels have facilitated the individual designers to develop open-source 3D models ready-to-be-sent in a 3D printer format. Open-source models have turned out to be a boon during this pandemic [17, 18]. The open-source files can be accessed and used by any individual or firm to respond to their own requirements. This has harnessed volunteerism in many of the global 3D printing firms, universities and other independent groups to provide emergency needs for local hospitals and frontline workers [11]. Aware of AM's flexibility in producing life-saving supplies, the hobbyists and functional 3D printing firms/labs worldwide have been working collectively on a common goal of safeguarding humankind [18, 19]. Food and Drug Administration (FDA) has emphasized that 3D printing community response and non-traditional manufacturing have helped to overcome the shortages of medical supplies during this pandemic, in the forms of PPEs, gears and other 3D-printed accessories in many parts of the world [20]. According to a report, to address the lack of PPEs and other medical requirements, the FDA has attempted working in partnership with the Veterans Affairs (VA), the National Institute of Health (NIH), and America Makes, to support the non-traditional manufacturing techniques, likely 3D printing. These collaborations have resulted in more than 348,000 3D-printed face masks and 500,000 3D-printed face shields for health care providers and others in need since March 2020 [20].

Table 1. Products produced by prominent manufacturing industries/organizations with 3D printing facility before and during the pandemic.

Sl. No	Manufacturer/ Organization	Domain	Products manufactured		Ref.
			Before pandemic	During pandemic	
1	Airbus	Aerospace	Aircraft components	Medical visors	[21]
2	Ford	Automotive	Automotive components	Respirators, ventilators, face masks and face shields.	[22]

3	General Motor	Automotive	Automotive components	Ventilators and its components	[23]
4	Nagami	Product Design	Furniture	Masks	[24]
5	Toyota	Automotive	Automotive components	Face shields and ventilators	[25]
6	Yingchuang Building Technique (Shanghai) Co., Ltd.	Construction	3D Printing Architecture	Isolation wards and quarantine shelters	[26]

4. 3D Printing in Medical Applications during COVID-19

Lack of medical equipment's and its components have resulted in a globally soaring COVID-19 mortality rate [9]. In addition to this, a significant strain has been placed on PPEs supplies required to protect the healthcare workers treating critically ill patients [27]. The medical requirement shortages are primarily due to the lack of preparedness in producing or stocking enough supplies for sudden and overwhelming demands. The failures in medical system to provide tests, care, and protection, increased with the growing numbers of infected people [9, 11]. Suppliers were unable to meet the rapid surge in demands for medical equipment's and PPEs caused by the contemporaneous outbreaks of the COVID -19 worldwide. Few reports from Italy depicted the ugliest side of the pandemic, where life-saving ventilators were allotted based on the best chances of survival and lottery systems [28]. To diagnose and treat the COVID-19 infected patients, medical equipment's crucially used are diagnostic test kits, PPEs, and ventilators [11]. This section gives an overview of how 3D printing has played a significant role in providing rapid solutions to answer the global shortage of medical requirements.

4.1. 3D Printed PPEs

PPEs act as a shield in between users (generally health care professionals) and pathogens. It is necessary for all the health care professionals to use PPEs to reduce the spread of pathogens during the pandemic like situations [29]. PPEs are subjected to the FDA enforcement guidelines, but citing an attempt to help greater availability of the PPEs during the public health emergency, FDA relaxed its guidelines. As per the new FDA guidelines for COVID-19 pandemic, it will not object to the distribution of improvised PPEs as long as they do not cause any "undue risk" [30]. With the FDA's relaxed guidelines on PPE regulation, there has been a clear indication for the need of 3D printed PPEs [31]. Owing to the AM's versatility, Ford Motor company was able to 3D print PPEs at its plant in Plymouth, Michigan, which resulted in the production of roughly one million face shields per week [32]. Czech-based Tech giant Prusa Research began sharing open-sourced face shield designs, allowing anyone with a 3D printer to download and use the design file to print [31]. Many hobbyists have 3D printed PPEs to help local hospitals with the severe shortages [32]. For the first time, 3D printer home-users' community has joined hands to produce PPEs in large numbers. It has been evidently proved that more than 180,000 users worldwide were able to produce up to 6 face shields in 10 hours, each on average, depending on the designs and capabilities of the printers possessed. Assuming that a country like Greece having about 500 printers, could produce more than 6,000 face shields in a single day and was enough to equip its nurses, doctors, rescuers, and staff working in contact with patients [29].

4.1.1. 3D printed Masks and Face Shields

Facemask is simply a wearable cover acting as a physical barrier to avoid contracting of pathogens through nose and mouth [9, 27]. A surgical mask is a loose-fitting disposable face cover. According to the FDA guidelines, masks like N95 and KN95 must have a close fit, and seal around the nose and face [33]. The Centres for Disease Control and Prevention (CDC) recommends the use of N95 masks for health care workers in contact with COVID-19 patients and suspects with symptoms [34]. However, theses masks too are not recommended for the multiple reuse as its filters are inseparable and must be disposed-off properly after its use. Using low-cost Fused Deposition Modeling (FDM) printers, members of global 3D printing community have designed and printed reusable facemasks frames with insertable filters [27]. Claire et al. [35] have printed 50 reusable masks for the Midwestern Trauma Centre, and have made design files available online. These researchers have used the polylactic acid (PLA) in an Ultimaker S3 FDM printer to produce the reusable masks. Grabcad-a-largest online community of designers, professionals, manufacturers, and students, have come up with the designs of reusable facemasks as revealed in Figure 3. and have allowed their designs to be open-source [36].

Figure 3. 3D representation and printed Grabcad reusable face mask [37].

FDM printers are the one used widely to produce the facemasks. To make SLA desktop printers contribute actively, 3D systems, a pioneer and the founder of Stereolithography (SLA), have designed a facemask comprising facemask body and filter cover as shown in Figure 4. The 3D systems call this mask as Stopgap facemask and have recommended using DuraForm ProX PA, PA 1101 and PA 2200 materials in their detailed instructions for use [38]. In California, a non-profit organization called Maker Nexus has used its 3D printers and laser cutters to produce masks for local hospitals using the open-source Prusa 3D printed shield design [19].

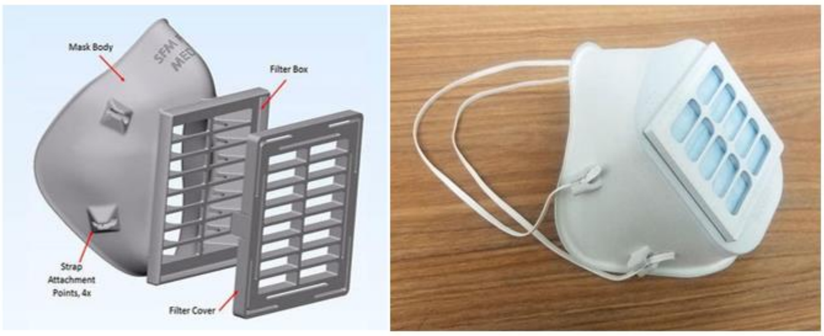

Figure 4. SLA printed 3D systems Stopgap face mask a) CAD representation b) Printed face mask [38].

Medical face shields are head-mounted devices worn as a physical barrier during aerosol-generating procedures such as oropharyngeal suction, respiratory physiotherapy or intubation [39].

Numerous kinds of Face shields fitting different head sizes were 3D printed for nursing homes and regional hospitals during the pandemic [40]. Dina et al. [41] 3D printed face shield frames using biopolymer PLA with available low-cost Prusa FDM printer and have assembled it with a transparent sheet. An American aerospace manufacturing company Blue Origin and 3D printer manufacturer Carbon have also contributed to producing the face shields [19].

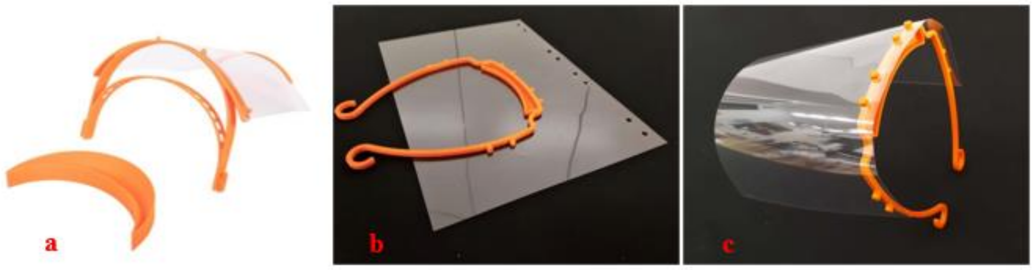

Figure 5. 3D printed (a) Prusa face shield [43] (b) and (c) 3DVerkstan face shield [42].

3DVerkstan, a 3D printing solution provider, has responded to the global shortage of face shields by printing the face shields as shown in Figure 5. The 3DVerkstan made these design files available open source for FDM printers. 3DVerkstan claim that the nozzle diameter of up to 1 mm and a layer thickness of 0.5 mm could be used with the polymer filaments such as PLA, CPE, PETG, and ABS for printing face shields [42].

As like facemasks, most of the face shields proposed were often to be made using FDM printers. The 3D Systems also have contributed to design a flexible type and form-fitting face shields, as shown in Figure 6. They have used their SLA printers and have made their design files available open access [44]. 3D systems recommend autoclavable and compatible with disinfectant cleaner medical-grade nylon as a feedstock material for printing reusable face shield [44].

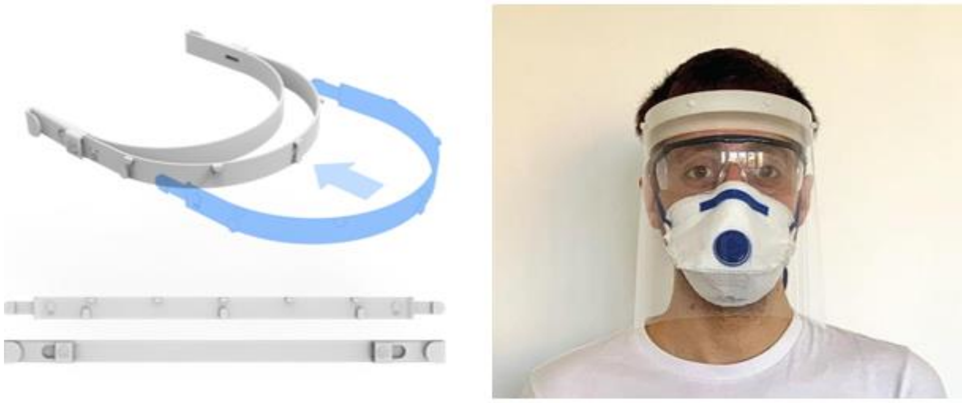

Figure 6. SLA printed 3D systems face shield by 3D systems [44].

During the later stages of COVID-19 outbreaks, most of the hospitals delayed the elective arthroplasty surgeries, and the helmets systems procured for these surgeries were sitting idle. Duke University Medical Centre modified these un-used helmets to fit as a PPE by using 3D printing techniques. This has set an example for an alternative way to tackle PPE shortage for frontline workers [45]. Otolaryngologists are generally at higher risk of infection during the mouth and nose examinations. Most of the face shields were not compatible with helmets used during the examination. In this context, Jaime et al. [46] used FDM 3D printers to print adapter to externally fit the face shield to Otolaryngologists helmets.

4.1.2. 3D Printed Respirator

Powered air-purifying respirators (PAPR) can provide most superior protection from the virus [45]. The N95 respiratory masks have advantages over surgical and cloth masks. They are tested for the right fit to ensure an adequate seal, to avoid air and tiny droplets entering through the edges of the mask into the breathing zone and are proved to be more than 95% efficient in filtering airborne particles as small as 0.3µm. To reduce the impending shortage of N95 masks, the George Washington University Hospital has developed reusable respirators with replaceable N95 filters. These respirators could be used with multiple filtration units. Respirators were trial printed with FDM printable materials such as PLA, ABS, and TPU. The PLA respirators with MERV 16 and MERV 13 sandwich filters were found to be most valuable options considering their fit, cost, cleaning, and sterilization protocols. Developers also claim that their proposed N95 reusable respirators could be a viable alternative to the regular N95 masks [33]. Concerned about the potential shortage of PARPs, which are to be used for intensive and sub-intensive care of patients suffering from COVID-19, Isinnova - an Italian firm has worked in partnership with Decathlon to convert Decathlons' Easybreath scuba mask into respirators using connectors [19]. Isinnova has called these connecters as Charlotte valve, and the 3D printable files can be downloaded from their website directly [47]. Easybreath scuba mask with Charlotte valve can be seen in Figure 7. Isinnova also has stated that, PLA filament with nozzle temperature of 205 – 210 0C, bed temperature 35 – 50 0C, and a layer thickness of 0.2 mm can be used in FDM printers for printing the Charlotte valves [47].

Figure 7. Easybreath scuba mask modified to PARP using Charlotte valve [47].

4.2. 3D Printed Nasopharyngeal Swabs

The SARS-CoV-2 virus that causes COVID-19 disease can be detected through respiratory samples by reverse transcription-polymerase chain reaction (RT-PCR) or other molecular methods [48]. Nasopharyngeals (NP) are the devices used to capture respiratory mucus, epithelial cells and release the mucus matrix into a transport medium. Transport medium can be analyzed to find viral RNA [49]. The NP swabs must serve three essential functions: (i) must pass through the nasal cavity easily and comfortably; (ii) must collect enough mucus to test for viral RNA, and (iii) should be capable of releasing the collected sample in a manner that will not interfere with the RT-PCR test [50]. The surge in COVID-19 testing has caused an acute global shortage of nasal swabs [51] and access to NP swabs remained a bottleneck for COVID-19 testing in some regions of the world [52]. Use of 3D-printed NP swabs to collect nasal samples for COVID-19 testing is feasible, acceptable to and is convenient for local production as well [51]. Formlabs, a 3D printer manufacturer and technology developer, has used its printers to manufacture up to 100,000 nasal swabs every day to tackle these shortages. Printed swabs were to be shipped to hospitals across the United States which needed supplies for early coronavirus detection [19]. Formlabs has used surgical guide resin which has been indigenously developed and specially designed for their printer [53]. Goldstein et al. [48] printed NP swaps using autoclavable surgical grade resin (Surgical Guide, FormLabs) and compared with the conventional Flocked Nasopharyngeal Swabs (FLNP). The 3D printed swabs displayed statistically identical results to standard FLNP in a head-to-head clinical trial, making it a viable option in COVID-19 testing requirements. These researchers have concluded that 3D-printing technology can provide an alternate strategy for swab shortages by facilitating a local solution to FLNP shortages [48]. Sarah et al. [12] printed nearly 2000 swabs using PLA in FDM printers and sterilized them using low-temperature plasma and these swabs have costed them as low as $ 0.05. Nicole et al. [52]

designed and printed the NP swab using Stereolithography (SLA) as exhibited in Figure 8. and made their design open access. These designed swabs were also able to absorb a significant amount of mucus and have passed the abrasion and handling tests.

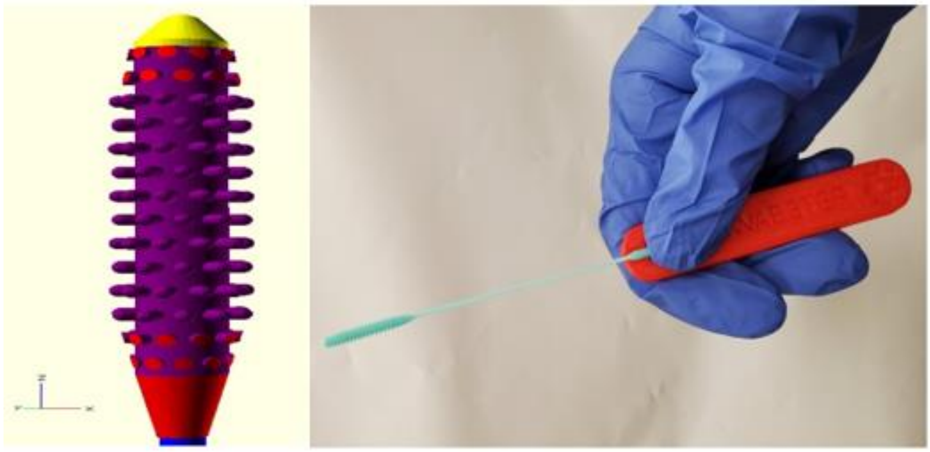

Figure 8. CAD representation and SLS printed NP Swab [52], Open access.

Ian et al. [50] developed lattice bulb NP swabs using Digital Light Synthesis (DLS). These lattice swabs showed efficiency in early clinical trials and met all necessary criteria for a NP swab. Pediatric nasopharyngeal swabs (mini swabs for kids) are a smaller, thinner, and more flexible version of NP swabs used for adults. Pediatric nasopharyngeal swabs faced a severe scarcity in supply during the Coronavirus pandemic than the adult swabs. Starosolski et al. [49] in Texas Children's Hospital printed NP swabs using surgical resin. Their work aimed to provide pediatric NP swabs for kids of 1-3 years of age. Printed mini swabs were subjected to tensile, torsion, flexural and fluid absorption tests after sterilization. Pediatric NP swabs have proven their usability and efficiency with increased mechanical properties while considering a trail on 40 human samples. This work was carried out using the 3D printers adopted by Radiology departments of Texas Children's Hospital for patient education and surgical planning with the available resources. This explained the degree of flexibility of 3D printing technology on offer to tackle the pandemic like situation. 3D printed swabs can also be used to diagnose other common upper respiratory tract pathogens, including respiratory syncytial virus, influenza virus, and Streptococcus pyogenes [51].

4.2. 3D Printed Ventilators and Valves

Severely infected COVID-19 patients need ventilators to support respiration [54]. Approximately 2.4 % of the COVID-19 infected patients need ventilators to support respiration. A mechanical ventilator supports the patient's respiration by providing positive pressure to the lungs [11]. Most recently, the first 3D printed ventilator was developed in Spain [40]. To quicken the process of design and development of the ventilators' critical and intricate components is the need of the hour, and the AM technology is the one with all capability to achieve it [40]. Through integrated manufacturing capabilities of additive manufacturing technology, assembly steps required for the ventilators can be minimized. With an agenda to develop critical parts for a low-cost ventilator, University of Minnesota has collaborated with a 3D printing service provider called Protolabs and have worked together on developing essential elements for low-cost ventilators [19].

A game-changing idea of splitting a single ventilator to two or more patients has been proved as an excellent solution for ventilator shortage [27]. A practical study in 2006 by Greg Neyman [55] indicated that ventilator splitters could be used to support respiration of 4 patients with a single ventilator. It has been proposed that a single ventilator can be quickly modified to support four individuals of up to 70-kg for a limited time during an alarming situation like multiple casualties with respiratory failure [55]. Dependency on conventional injection moulding technique for producing the ventilator splitters costs more than a week. Using 3D printed ventilator splitters, a single ventilator can accommodate multiple patients in life-saving situations, as demonstrated in Figure 9. Formslabs and Prisma Heath South Carolina have successfully 3D printed these splitters [19]. The ventilator circuit splitter team [56], a medical professional group in the USA, has designed ventilator splitters and made design files open access. The ventilator circuit splitter team has also discussed on print parameters and verification guidelines after printing according to which the FDM printer with nozzle diameter of 0.4 mm, 100% infill, 0.2 - 0.3 mm layer height and print direction of upside-down Y-direction for circuit splitters and an upright position for limiters can be used with a bio-compatible polymer [56].

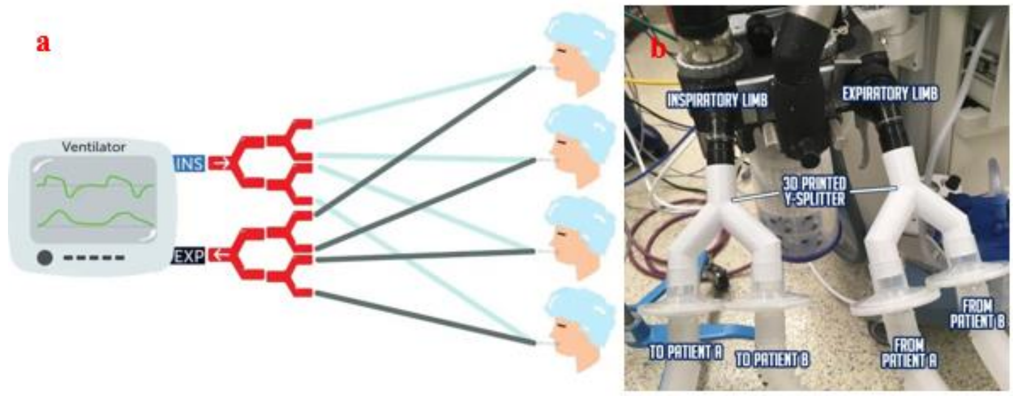

Figure 9. Ventilator splitter (a) schematic representation (b) splitters connected to a shared ventilator [56].

Ventilator valves are the attachments that are used to deliver oxygen at fixed concentrations for patients with acute respiratory distress, including the COVID-19. In 2020, a hospital in Italy with nearly 250 critically ill COVID-19 patients on ventilator support ran out of Ventilator valves needed to connect the patients to the machines. Due to the unexpected increase in demand, the original suppliers could not meet the high demand. Isinnova used 3D printing as a quick response to the situation and has successfully printed ventilator valves [56]. Ventilator valves were prototyped in short time duration of 8 hours, produced 100 valves in a day, and each valve costed less than € 1 [57-58]. Printed ventilator valves have saved the lives displaying the rapid response capabilities of AM. Isinnova produced ventilator valves prioritizing life-and-death situation over the copyrights and medical issues, making them unable to share relevant information and design publicly [58].

AM/3D printing technology was not just limited to address the shortage of PPEs and other devices during COVID-19 pandemic. Stephanie et al. [6] have predicted that the 3D printing will be revolutionizing the pharmaceutical industry in the direction of drug research, development, and production applicable to Coronavirus. A robust and dynamic drug supply system will be the key to manage future crises. Wen-Kai et al. [15] trust that the 3D printing can be used as a decentralized and flexible drug production system with insufficient logistical infrastructure and supply chains. 3D printing in drug production systems can also be used in disease hot spots with extensive quarantine measures or in a rural health care centres at remotest of locations [15]. Martin et al. [18] suggested that by printing 3D models for planning complex orthopaedic, brain and abdominal tumour surgeries and more, reduces the patients' admission time in the hospital. This, in turn, reduces both the risks of intra-hospital COVID-19 infections and percentage of bed occupancy. The COVID-19 contagion can be controlled by tracking, monitoring, and early intervention at home. To provide a home-based solution, Mohammedhusen et al. [59] have developed a bracelet prototype to detect biomedical parameters such as low blood oxygenation or high temperature using 3D printing. These biomedical parameters are instrumental in monitoring the patient with a viral infection. This bracelet is proficient in tracking the number of other bracelets in the proximity and can be used to monitor user’s in-home quarantine. Using Optomec's Aerosol jet technology printed low-cost sensors, researchers at Carnegie Mellon University have developed a device capable of identifying antibodies in 10 to 15

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seconds. And the device has been in the trial and testing stage for Coronavirus patients [3]. To understand the long-term damage caused by Coronavirus companies like Axial3D, Belfast Health, and Social Care Trust have printed lungs models. These lungs models have been prepared using the CT scan data taken on 14th day of infection and were used to demonstrate the various effects of the virus [3]. A San Francisco-based bioprinting company Prellis Biologics explored how synthetic bio-printed lymph nodes can be used to produce COVID-19 fully human antibodies [3]. To reduce the healthcare professionals' risk while swab testing, robotics researchers from the University of Southern Denmark have developed the world's first fully automated robot to carry out throat swabs tests for COVID-19 [3].

5. 3D printing in Non-Medical Applications of COVID-19

Direct contact with commonly touched surfaces likely elevator buttons, door handles and computer keyboards can spread viral diseases [60]. In Paris, to lower the risk of COVID-19 contamination by limiting direct contact, François et al. [60] have found success in printing the hands-free door hooks, openers and button-pushers which were later dispatched to Greater Paris University Hospitals and other state institutions. Materialize, a 3D printing and software solution firm, developed several hands-free door openers (Figure 10) and made these designs available open source [61].

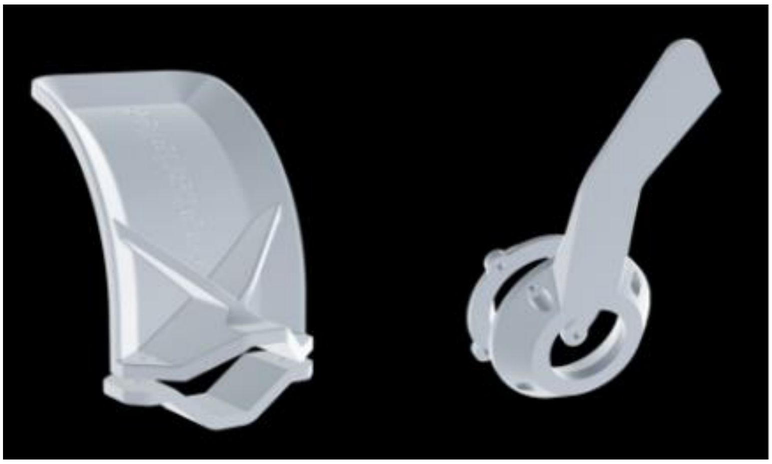

Figure 10. 3D printable hands-free door opener from Materialise [61].

Thermal scanning using handheld infrared thermometers has been the most common method for thermal screening in public places. Personnel involvement in thermal screening has raised concerns as there is a possibility of violating safe distance between two or more people [62]. Abuzairi et al. [62] have printed Infrared thermometer using 3D printing and made designs as open source to eliminate human dependency on thermal screening. The developers call this 3D printed Infrared thermometer as i-Thermowall and can be seen in Figure 11 [62].

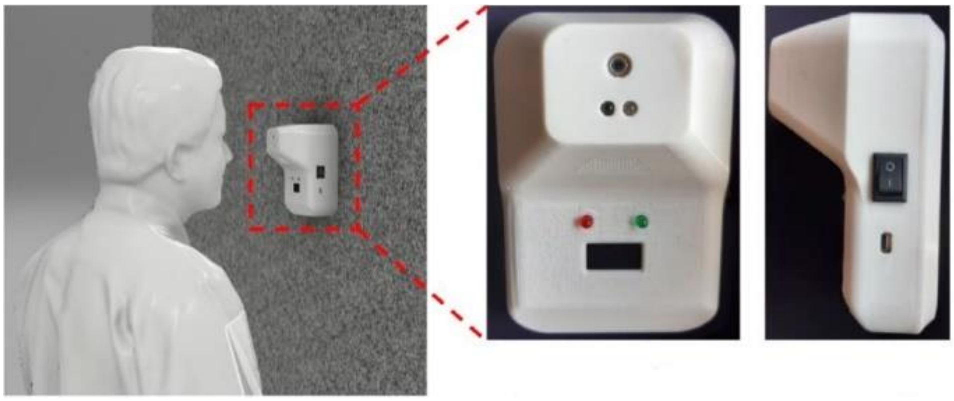

Figure 11. 3D printed Infrared thermometer (i-Thermowall) [62]; Open access.

6. 3D Concrete Printing and COVID-19 pandemic

The construction sector is one of the largest contributors to the global economy yet has exhibited notably poor productivity compared to other sectors. It has always been a challenge for global infrastructure and construction industry to meet the ever-increasing global demands [63]. Post COVID-19 outbreaks the demand for isolation wards and quarantine shelters skyrocketed and meanwhile, the disordered and disrupted supply chains posed a bigger challenge for the construction sector. Automation in construction technology has shifted the prime focus towards itself since few years. The recent trends in 3D printing include its advent in construction technology. The 3D printing using concert and cob (an earth-based material) has proved its superiority over conventional construction methods. The primary advantages are reduced costs and time required for the construction of rapid isolation wards or shelters (350 sq. ft. house can be built within a week time) [64-66]. In the pre-COVID era, there are few examples of using 3D printing in construction of houses and shelters [64]. However, in 2018, a group of IIT Madras faculty members had collaborated with a start-up company Tvasta to build a 350 sqft house in a week inside in the university campus [67]. The same Tvasta team in 2020 has built 600 sqft house inside IIT Madras and assured to build houses in 3 weeks. Tvasta says that green strength of 3D printed concrete can be achieved in a few minutes, and the overall structure will be ready by 7-10 days [68]. Nonetheless, the literature reveals that the reduced bonding strength between successive layers, increased deformation layers and dry-shrinkage issues are some of the challenges to be overcome significantly for a better 3D printed architecture [64-65]. Very few attempts have been made in this regard to develop 3D printed isolation wards/quarantine shelters for coronavirus patients and medical staff. In February 2020, Winsun, a China-based company has 3D printed isolation wards for COVID-19 patients using concrete and recycled materials, of which each of the structures measuring 10 square meters in area with a height of 2.8 meters. It has been claimed that the units have been built according to the standards of even withstanding earthquake and extreme conditions [69].

5. Summary and Conclusions

3D printing has allowed the manufacturers to contribute towards the fight against COVID-19 pandemic differently. Being a flexible manufacturing technology, AM has proved its efficacy by answering the global PPEs shortage remarkably in the least possible time. Distributed manufacturing capabilities of AM have truly helped in fulfilling local requirements when supply chains were severely disrupted. Several open-source 3D printable designs are being created and shared globally for collective efforts and these open-source files are being used by universities, professionals, hobbyists and several other manufacturing firms to respond and translate themselves in responding to the medical and

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non-medical needs. The translation was and is possible owing to the unique flexible nature of AM. Through 3D printed splitters, the global shortage of ventilators was kept down to a possible extent. 3D concrete printing has been deployed to remotely construct quarantine shelters during the COVID-19 pandemic as it requires less human intervention and can construct with least possible time. The 3D concrete printing and its related technology have not yet been developed wholly to replace the conventional methods. However, if the limitations and challenges involved are overcome, it can be used as a reliable construction technology in the future to handle the next contagion. Apart from these solutions, 3D printing has also been used for operation planning, prototyping and testing during this pandemic. The scope of AM in this crisis has subsequently increased with the development of much affordable and more reliable 3D printing technology.

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Appendix A

To provide a one-stop solution to the readers, hobbyists and professionals in downloading open-source COVID-19 related design files, authors have provided few available open-source files in Table 2.

Table 2. Few available Open-source 3D printable files for hobbyists or professionals.

File provider	Description	Link to download
Copper3d	Reusable face mask	https://copper3d.com/hackthepandemic/
Grabcad	Reusable face mask	https://grabcad.com/library/breathing-mask-with-screw-in-filters-version-2-1
Lowell	Reusable face mask	3D-Printed Masks – Lowell Makes
3D Systems	Reusable face mask	https://www.3dsystems.com/COVID-19-response#face-Mask
Bellus3D	Mask filter holder	https://bellus3d.com/solutions/facemask.html
NASA JPL	Respirator	https://github.com/nasa-jpl/COVID-19-respirators/tree/master/design1-performance/STL_Files/
Modeldesign	Retains the Visor	https://www.modeldesign.ma/download/modeldesign_clips_pour_visiere/
Maltese Man	Holds face shield	https://www.myminifactory.com/object/3d-print-114808

Materialize	Hands-free door openers	https://www.materialise.com/en/hands-free-door-opener
corona-virusmakers.org	Face shield	https://www.coronavirusmakers.org/validacion-nacional-visera-doc-ficheros/
EOS	Face shields	https://3dagainstcorona.eos.info/how-3d-printing-helps-with-corona#content5e876011cbd84
3DVerkstan	Face shield	https://www.youmagine.com/designs/protective-visor-by-3dverkstan
Prusa	Face shield	https://www.prusaprinters.org/prints/27318-prusa-protective-face-shield-cover-rc1-wip#_ga=2.137673648.1814275440.1610550741-724956520.1610550741
3D Systems	Face shield	https://www.3dsystems.com/COVID-19-response#faceShield
DMRC	Face shield	https://dmrc.uni-paderborn.de/content/downloads
Nathan Schenk	Safety goggles	https://github.com/schenkzoola/WalaGoggles
Nicole Gallup et al.	NP swab	https://osf.io/z5jgu/
Copper3d	Ventilator splitters	https://copper3d.com/hconnector/
Ventsplitter.org	Ventilator splitters and limiters	http://ventsplitter.org/
Grabcad	Ventilator valve	https://grabcad.com/library/respirator-free-reanimation-venturi-s-valve-1/details
Isinnova	Charlotte valve	https://www.isinnova.it/easy-COVID19-eng/
Tomy Abuzairi et al.	iThermowall	https://zenodo.org/record/4127545#.YAFMU9gzaUk

Disclaimer: Authors intended to provide a useful resource only. Authors are neither related to the open-source files nor promoting them. Provided, open-source links are subjected to the provider's terms, conditions, and guidelines of usage. Authors are not responsible for the outcomes of open-source materials.

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