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Electrically Conductive Fused Deposition Modeling Filaments: Current Status and Medical Applications

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Abstract: Fused Deposition Modeling (FDM) is one of the most popular three dimensional (3D) printing techniques especially among researchers. Recently, FDM has been widely developed and improved in many areas. One of these improvements is the introduction of electrically conductive filaments. In general, conductive filaments are usually made of conductive polymer composites. These composites consist of a thermoplastic material blended with carbon-based materials. The quantity of commercially available conductive filaments has grown significantly in recent years. This paper presents a sample of currently available conductive filaments (eight filaments were chosen). These samples were compared by measuring resistance value and highlighting resulted defects of each sample. Additionally, this paper searched and reviewed articles that used conductive FDM filaments in medical applications. These articles were collected and summarized in terms of name of filaments were used, the specific function of the printed conductive object, and name of the printer used to print the conductive object. In conclusion, the main purpose of this project is to facilitate the work of future medical researchers who would like to use commercially available conductive FDM filaments.

Keywords: fused deposition modeling (FDM); conductive filaments; medical applications

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1. Introduction

Three dimensional (3D) printing, also referred to as additive manufacturing (AM), is the process of building 3D objects layer by layer using 3D model. It is a newly developed science which has great potential and can be increasingly adopted in various areas, including medical applications. Although there are several methods of 3D printing, fused deposition modeling (FDM) is considered one of the most popular, efficient, and cost effective technique [1,2]. FDM can also be referred to as fused filament fabrication (FFF) or material extrusion devices. It is a 3D printing process where a filament is pushed by the extruder into the hot end and through a heated nozzle which melts the filament and deposits it in a thin layer of molten material on a predefined path on the xy-plane and adds layer by layer in the z-direction [2]. The rate of pushing the filament is controlled by the extruder. There are two main extruder setups to push the filament are the Bowden tube and the direct drive. The main difference between these techniques is the way in which the filament is being pushed into the heated nozzle. In a Bowden tube setup, the extruder is mounted on the frame of the printer and push–pulls the filament into the hot end through a long polytetrafluoroethylene tube (called PTFE or Bowden tube). In a direct drive system, the extruder is mounted on the print head and push–pulls the filament directly into the hot end [3].

The quantities of commercially available FDM materials have grown significantly in recent years, while the cost continues to decrease. Thermoplastic filaments are the main classification of these filaments. Additionally, these filaments could be divided into subcategories, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polyethylene terephthalate glycol-modified (PETG), thermoplastic polyurethane (TPU), polyvinyl alcohol (PVA), polyvinylidene fluoride (PVDF), and nylon. PLA is the most popular filament because it is relatively easy to print and available in different colors and styles which make it the best option for beginners. However, PLA is very brittle and cannot be used in applications required flexibility. ABS is the second most used FDM filament and exhibits excellent mechanical properties, such as impact resistance and strength. TPU is the most flexible FDM filaments; however, this flexibility makes it more complicated to print [4,5].

Conductive filaments are usually made of conductive polymer composites. These composites consist of a thermoplastic base material blended with carbon-based materials, such as carbon black, graphene, graphite, carbon nanotubes, graphite sheet, and other carbon materials. The availability of different composites generates a variety of mechanical, electrical, and thermal properties. Even though this variability adds complexity to the printing process as it differs from one filament to another, these different properties open the door to discover and create more applications. These materials are very well suited for the fabrication of truly 3D conductors [6]. Table 1 lists the most popular commercially available conductive FDM filaments.

Table 1. Most popular commercially available conductive FDM filaments.

Filament	Material	Resistivity Ω.cm
Proto-Pasta [7]	PLA doped with carbon black	(x/y): 30 Ω.cm(z): 115 Ω.cm
Black Magic Graphene [8]	PLA doped with graphene	0.9 Ω.cm
Palmiga PI-ETPU 95-250 [9]	TPU doped with carbon black	Less than 800 Ω.cm
Conductive Filaflex [10]	TPU and doping information could not be found	3.9 Ω.cm
Multi3D Electrifi [11]	Metal-Polymer composite consists of biodegradable polyester doped with cooper	0.006 Ω.cm
Amolen [12]	PLA and doping information could not be found	1.5 Ω.cm
Filoalfa Alfaohm [13]	PLA doped with carbon nanotubes	(x/y): 15 Ω.cm(z): 20 Ω.cm
3dkonductive [14]	PLA doped with carbon black	(x/y): 23 Ω.cm(z): 53 Ω.cm
Sunlu ABS [15]	ABS and doping information could not be found	10^3 to 10^5 Ω.cm
NinjaTek Eel [16]	TPU doped with carbon black	1.5×10^3 Ω.cm
Koltron G1 [17]	PVDF doped with aros graphene	2.0 Ω.cm
BlackMagic Flexible TPU [18]	TPU doped with graphene	Less than 1.25 Ω.cm

This paper searched and reviewed medical application articles that used commercially available conductive FDM filaments. These articles will be summarized and discussed in terms of the names of filaments used, the specific function of each 3D printed object, and the names of printers used to print these objects. Additionally, this paper will print a sample of some of the currently available conductive filaments. These samples will be compared mainly regarding two main points: the measured resistance of the printed sample and the practical difficulty of printing these samples. In conclusion, the main purpose of this project is to facilitate the work of future medical researchers who would like to use conductive filaments.

2. Materials and Methods

2.1. Searching for Articles and Commercially Available Conductive Filaments

A literature search was performed using Google Scholar with one and/or more of the following keywords “3D print”, “FDM”, “conductive filament”, “medical applications”, and “specific name of the conductive filament”. Commercially available conductive filament searches were accomplished using the following websites: Google, Amazon, AliExpress, All3dp, Filament2print, Creativetools, and filament manufacturer websites.

2.2. 3D Printing of Conductive Filaments

2.2.1. Printing Materials, Printing Settings, and Printer

This study tested eight commercially available conductive FDM filaments with a 1.75 mm diameter. These filaments are Proto-Pasta, Palmiga PI-ETPU 95-250, Multi3D

Electrifi, Conductive Filaflex, Filoalfa Alfaohm, 3dkonductive, Amolen, and Sunlu ABS. Proto-Pasta is one of the most popular conductive filaments. It comprises a combination of milled carbon fibers and high-performance heat-treatable PLA [7]. Palmiga PI-ETPU 95-250 is a flexible, rubber-like, TPU filament filled with carbon fiber which makes it electrically conductive. It possesses a 95A shore hardness [9]. Conductive Filaflex is a flexible, electrically conductive TPU filament with a 92A shore hardness. According to its manufacturer, it is a good filament for the creation of wearable devices [10]. Multi3D Electrifi is a non-hazardous, proprietary metal–polymer composite that consists primarily of biodegradable polyester and copper [11]. Filoalfa Alfaohm could be used for the production of components that need to carry electricity and can be easily printed with most 3D printers. It is a completely non-toxic and odorless up to high temperatures [13]. Amolen is an electrically conductive PLA filament with a solid, consistent, dark black color and is compatible with most FDM 3D printers [12]. 3dkonductive is a highly filled PLA material developed for good printability and high conductivity [14]. Sunlu ABS has good mechanical properties and toughness [15]. All eight filaments were printed using a 3D FDM printer called Qidi Tech X-Plus and its corresponding slicer program [19,20]. It is an enclosed printer with two interchangeable direct drive extruders with 0.4 mm nozzle diameter. The default extruder is capable of printing general material, such as PLA, ABS, and TPU. The second extruder is a high temperature extruder (printing temperature up to 300 °C), which is designed to print advanced material, such as nylon and carbon fiber. Table 2 explains which printing settings were used for each filament. There were general printing settings used for all samples: 1.5 mm retraction distance, 30 mm/s retraction speed, 0.2 mm layer height, and 20% infill density. Three samples were made for each filament (long, square, and cylinder).

Table 2. Printing settings.

Filament	Nozzle Temperature	Printing Speed in	Build Plate Temperature
Proto-Pasta	206 °C	45 mm/s	60 °C
Palmiga PI-ETPU 95-250	220 °C	30 mm/s	60 °C
Multi3D Electrifi	160 °C	15 mm/s	0 °C
Conductive Filaflex	250 °C	30 mm/s	60 °C
Filoalfa Alfaohm	220 °C	20 mm/s	50 °C
3dkonductive	220 °C	60 mm/s	60 °C
Amolen	220 °C	45 mm/s	50 °C
Sunlu ABS	240 °C	50 mm/s	110 °C

2.2.2. 3D Models

The goal was to design three 3D models (long, square, and cylinder) with similar volumes. Long design dimensions are 10 by 10 mm for the base and 100 mm for length (x = 10 mm, y = 10 mm, and z = 100 mm). Square design consists of similar base and length dimensions equalling 21.54 mm (x = 21.54 mm, y = 21.54 mm, and z = 21.54 mm). The cylinder design has a base with a radius equalling 12.2 mm and its length equals 21.54 mm (r = 12.2 mm and z = 21.54 mm). Tinkercad was used to create these models [21].

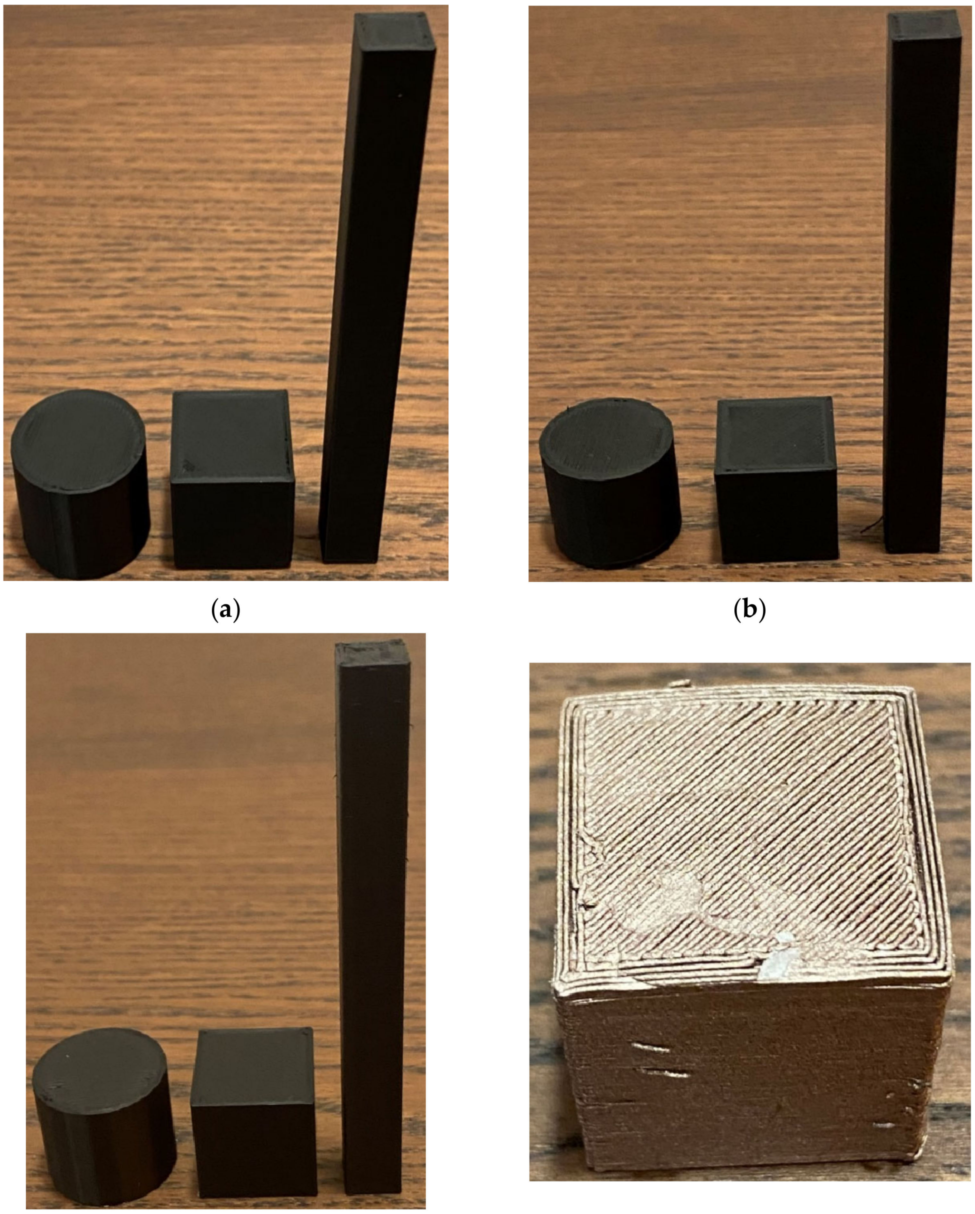
2.2.3. Measured Resistance Values of the Printed Samples

The resistance values of the 3D printed samples were measured using a smart digital multimeter (GVDA GD128, resolution 0.1 Ω for values below 1 kΩ and accuracy ± 1% + 5) [22]. These measurements were carried out by placing multimeter leads: one on the top surface and the other in the bottom surface of the long and cylinder samples and one on any surface and the other in the opposite surface of the square samples.

3. Results

3.1. Printed Samples of the Selected Conductive Filaments and Their Measured Resistances

Figure 1 shows printed samples for each conductive filament and Figure 2 highlights some physical defects that occurred during the printing of these samples. Table 3 lists the values of measured resistance for each sample. Three samples have been printed for each filament except Multi3D, as this filament sometimes clogged in the extruder. Unfortunately, the only square sample was printed for Multi3D.



(**a**) (**b**) (**c**) (**d**)

Figure 1. *Cont.*

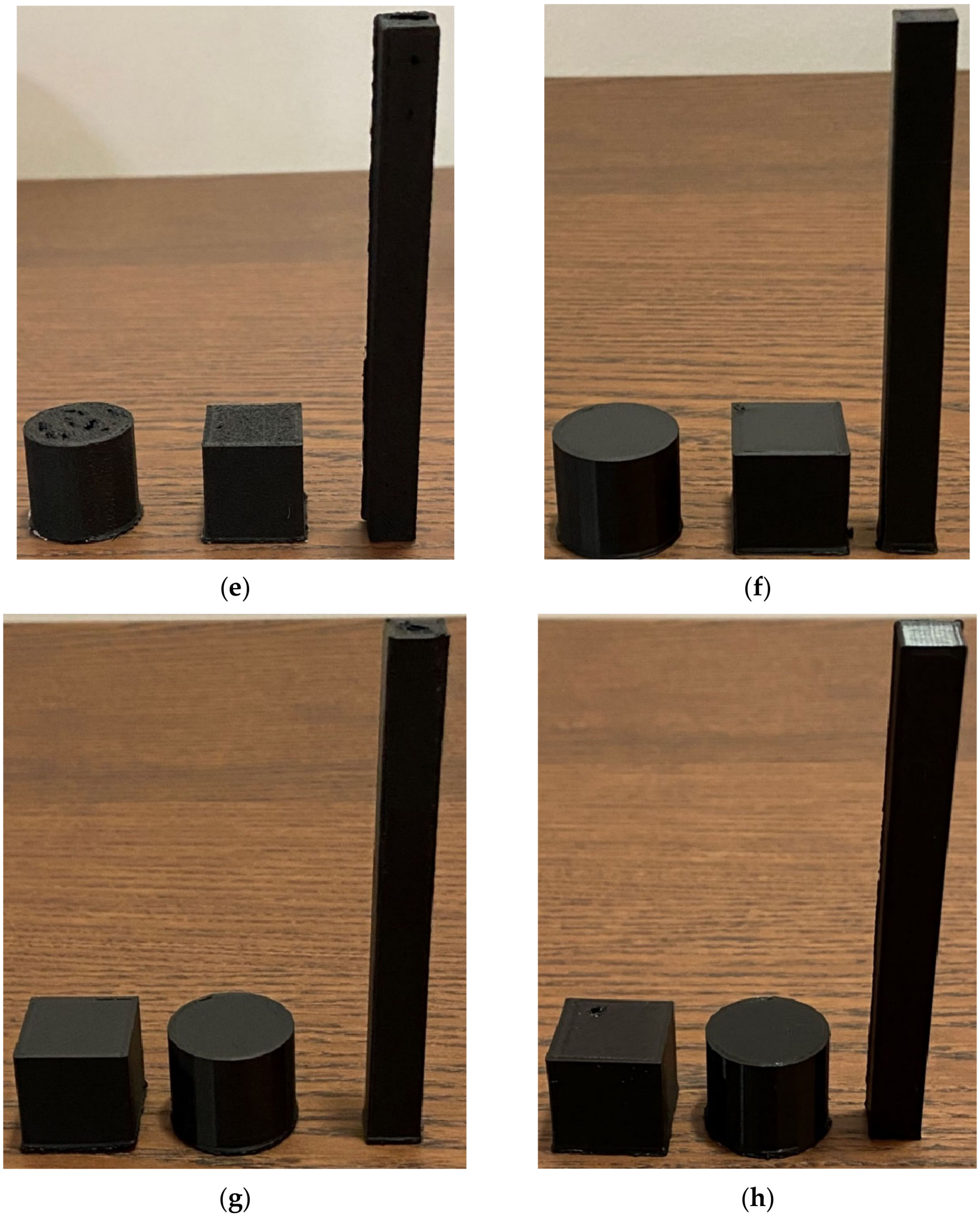


Figure 1. Printed samples of the following conductive filaments: (**a**) Proto-Pasta; (**b**) Filoalfa Alfaohm; (**c**) Palmiga PI-ETPU 95-250; (**d**) Multi3D Electrifi; (**e**) Conductive Filaflex; (**f**) Sunlu ABS; (**g**) Amolen; (**h**) 3dkonductive.

Table 3. Approximate values in kΩ of the measured resistance for printed samples.

Filament	Measured Resistance in kΩ		
	Sample1 (Square)	Sample2 (Cylinder)	Sample3 (Long)
Proto-Pasta	~0.7	~1	~1.3
Palmiga PI-ETPU 95-250	~2	~6	~7
Multi3D Electrifi	~0.05	NA	NA
Conductive Filaflex	~0.5	~1	~1.5
Filoalfa Alfaohm	~0.4	~0.6	~1
3dkonductive	~20	~25	~60
Amolen	~6	~13	~50
Sunlu ABS	~700	~3000	~4000

3.2. Medical Applications Articles which Used Conductive Filaments

Table 4 lists the medical applications studies that used commercially available conductive filaments in their projects. This table will highlight the following: the name of the used filament, the specific application of the printed object, and the name of the used printer to print the conductive object.

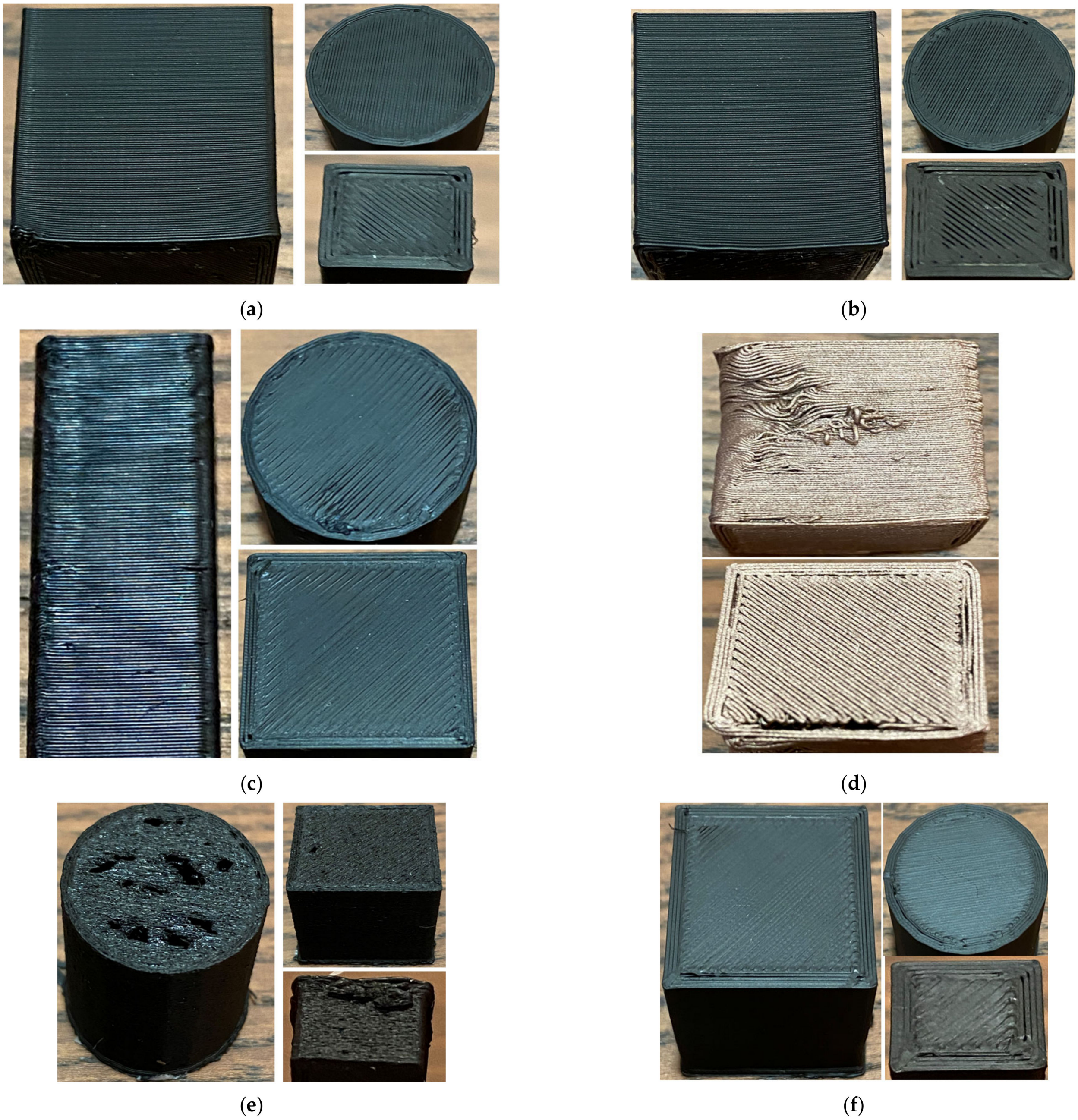
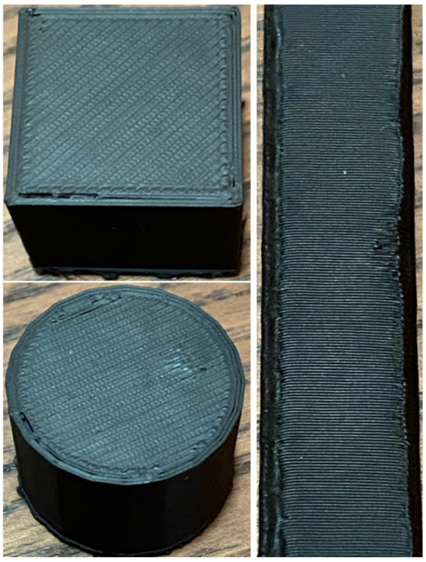
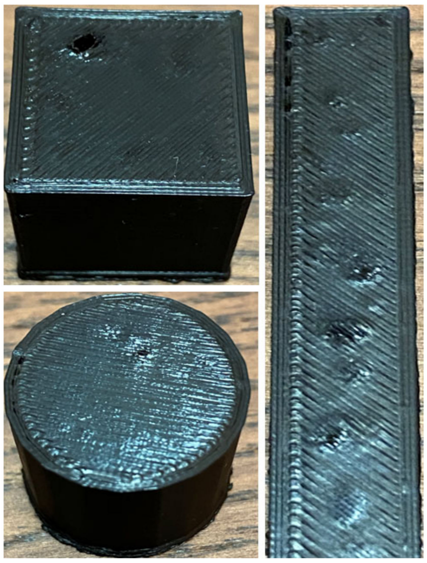


Figure 2. *Cont.*



(g)



(h)

Figure 2. Physical defects of the printed samples for the following conductive filaments: (**a**) Proto-Pasta; (**b**) Filoalfa Alfaohm; (**c**) Palmiga PI-ETPU 95-250; (**d**) Multi3D Electrifi; (**e**) Conductive Filaflex; (**f**) Sunlu ABS; (**g**) Amolen; (**h**) 3dkonductive.

Table 4. Medical applications articles that used conductive filaments.

Specific Application	Filament	Printer	Reference
EMG sensor	Proto-Pasta	Ultimaker 3 ***	[23]
Electrochemical detection of metals in biological samples using 3D printed electrode		Graber i3 RepRap	[24]
Planar resistance temperature sensor		Ultimaker 3 ***	[25]
Anthropomorphic phantom of the axillary region—bone structure		Ultimaker 3 ***	[26]
Integrated strain sensor inside a 3D printed coil spring—low cost basketball 3D printed prosthetic hand with haptic feedback		Ultimaker S5	[27]
Integrated strain gauge piezoresistive sensor		Not mentioned	[28]
Semi-wet spiked biopotential electrode with gel-filled conductive polymer cap		FlashForge Creator Pro	[29]
Electrochemical immunosensors for virus detection electrode and its application to detect Hantavirus Araucaria nucleoprotein (Np)		Graber i3 RepRap	[30]
Strain sensor for structural health monitoring		Prusa i3 MK3	[31]
Flexible resistive strain sensor for bending and contact feedback integrated into soft actuators and robotics		LulzBot TAZ 5 ***	[32]
Dose monitoring in a syringe-less wearable infusion pump		M3D Micro	[33]
Visually augmented audio-tactile graphical map with integrated capacitive codes		Felixprinters Felix Pro 1	[34]
Medical electrodes—ECG and TENS		Anet A8	[35]

Table 4. *Cont.*

Specific Application	Filament	Printer	Reference
Biocompatible, biodegradable, dielectric-conductive microsystems—resistors, capacitors, inductors, cantilevers, and electrohydrodynamic liquid ionizers		MAKEiT PRO-M	[36]
Electrochemical sensor for simultaneous dual monitoring of serotonin overflow and circular muscle contraction		Wanhao duplicator 4	[37]
Single-lead ECG dry electrodes and heart rate estimation for short term wireless ECG monitoring		Anycubic i3 Mega S	[38]
Human lung airways physical replicas		LulzBot TAZ 6 ***	[39–42]
Creating 3D printed fingerprint artefacts		Prusa i3 MK2 ***	[43]
Breast tumor phantom		Ultimaker 3 Extended ***	[44]
A multi-sensory interactive map for visually impaired children		Not mentioned	[45]
Patient-specific endovascular aortic repair (EVAR) stent-graft		DIYElectronics Prusa i3	[46]
Stiffness control and shape modulation of soft actuators and its potential in soft robotics		QIDI Tech I	[47]
Dose monitoring of a self-powered insulin patch pump		Micro M3D	[48]
Capacitive shear and normal force sensor using a highly flexible dielectric		Diabase H-Series ***	[49]
Contact lens with two spatially separated 3D printed electrodes used to enhance ophthalmic drug delivery via iontophoresis		Not mentioned	[50]
Multi-functional bioelectrodes for several advanced electrochemical devices, including glucose/O2 enzymatic biofuel cells	Proto-Pasta + Amolen	Flashforge Creator Pro	[51]
Integrated all 3D printed electrochemical microtitration wells (e-wells) for direct quantum dot-based (QDs) and enzymatic bioassays	Proto-Pasta + 3DEdge ABS **	Flashforge Creator Pro	[52]
On-field determination of Antipsychotic Drug Quetiapine fumarate (QF) via voltammetric mode		Flashforge Creator Pro	[53]
Breast Phantom for microwave imaging	Proto-Pasta + 3D-Prima conductive ABS **	Not mentioned	[54]
Wall-Jet flow cell for high performance liquid chromatography-amperometric analysis: application to the detection and quantification of new psychoactive substances (NBOMes)	Proto-Pasta + BlackMagic Graphene ****	ZMorph VX	[55]
Application of cold plasma in oncology—high voltage electrode of a dielectric barrier discharge single-channel plasma jet		Leapfrog Creatr HS	[56]
Custom ECG Electrodes to monitor human and canine heart rate during animal-assisted therapy	BlackMagic Graphene ****	Lulzbot Mini ***	[57]
Nanocarbon/Polylactic acid electrode—photoelectrocatalytic hydrogen evolution reaction		Prusa i3 MK3	[58]
Glucose monitoring sensor		MakerBot ***	[59]
Microfluidic membrane-less enzymatic biofuel cell		CreatBot D600 Pro	[60]

Table 4. *Cont.*

Specific Application	Filament	Printer	Reference
Integrated and automated electro-microfluidic viscometer that mimics Ostwald viscometer		FlashForge Creator Pro	[61]
Gelatin solution and graphene-based interdigitated circuit nerve regeneration conduits for electrical transdifferentiation of mesenchymal stem cells		LulzBot TAZ 6 ***	[62]
Paper-based microfluidic cassette for 2D paper chromatography and paper spray mass spectrometry for drug metabolism analysis in urine		Ultimaker 3 Extended ***	[63]
Soft surface EMG sensing structures	BlackMagic Flexible TPU ****	Flashforge Creator Pro *	[64]
Thin and flexible capacitive force sensor based on anisotropy that could be implemented on biomedical and soft robotic applications	Palmiga PI-ETPU 95-250	Flashforge Creator Pro *	[65]
Soft robotic monolithic unit for haptic feedback devices		Flashforge Creator Pro *	[66]
Soft surface EMG sensing structures		Flashforge Creator Pro *	[67]
Force sensor—detect muscle contraction using force Myography		Flashforge Creator Pro *	[68]
Whisker inspired flexible resistive strain gauges-based tactile sensor		Flashforge Creator Pro *	[69]
Integrating resistive deformation, binary, force, and vibration sensors in components		FlashForge Dreamer	[70]
Force sensors to encode pressure data from the shoe while it was in use to help creating smart shoe soles iterative personalization		Ultimaker 2+	[71]
Flexible capacitive force sensor		Ultimaker 3 ***	[23]
Resistive soft sensor skin for static contact pressure measurement between a hand and an orthosis		Ultimaker 3 Extended ***	[72]
Metamaterial capacitive sensor array for the detection of normal forces on curved deforming surfaces common to both the soft universal jamming gripper and human elbow wearables	Palmiga PI-ETPU 95-250	BCN3D	[73]
Flexible capacitive and resistive sensors for electroactive polymer, soft actuators, and flexible sensors		Lulzbot Taz 6 ***	[74]
Smart 3D printed textile piezoresistive sensor that could be used in breath rate measurement without an extra pulse belt		Prusa i3 MK3	[75]
Resistive sensor integrated into proprioceptive bellow actuator to provide real time position feedback and force estimation for soft robotics		Not mentioned	[76]
Flexible capacitive pressure sensor integrated into physical interfaces for wearable robots		E3D Toolchanger	[77]
Flexible fingertip force strain gauges-based sensor that measures normal and shear interactions forces resulted from deformations of the thumb and index		Diabase H-Series***	[78]
Bioinspired soft pneumatic actuators with built-in resistive pressure and position sensors, which could be printed with and used in soft robotics		QIDI Tech I	[79]

Table 4. *Cont.*

Specific Application	Filament	Printer	Reference
Flexible capacitive force sensor that could be implemented into 3D printed objects, such as soft robotic and prosthetic devices	Palmiga PI-ETPU 85-700+ **	Flashforge Creator Pro *	[80]
3D printed thermal mass flow sensor based on one heater element and two resistive thermal sensors		Flashforge Creator Pro *	[81]
Flexible piezoresistive shear and normal force sensor that measures the mechanical deformation of the finger tissue		Diabase H-Series ***	[82]
An artificial cellular finger with embedded capacitance based pressure sensor on the fingertip	Multi3D Electrifi	SeeMeCNC RostockMax Delta ***	[83]
3D printed soft fingertip with embedded tactile capacitive sensor for touch feedback in robotics/prosthesis applications		Ultimaker S5	[84]
Conformal flexible wearable antennas for breast cancer electromagnetic hyperthermia treatment		Leapfrog Creatr HS	[85]
Cooperative healthcare sensing robots with origami-inspired robotic structures to evaluate patients' muscle functions through gait analysis (Plantar pressure mapping) and EMG sensing robotic fingers		Tenlog TL-D3 Pro	[86]

* Extruders of these printers were upgraded by users. ** These filaments are not currently available and might be discontinued, obsolete, or not enough information could be found about their commercial availability. *** These printers might be discontinued, obsolete, or a newer version has been developed. **** These filaments currently out of stock.

4. Discussion

According to Table 4, most articles used conductive filaments in sensing and measurements applications [23–25,27–38,45,47–53,55–61,63–86]. Some articles used these filaments to build phantom and replicas [26,39–44,54] and the rest used these in therapy and treatment devices [46,62]. On the other hand, Proto-Pasta was noticeably the most used conductive filament [23–56] and Palmiga PI-ETPU 95-250 was the second most used filament [65–79]. Other filaments that were used are BlackMagic Graphene [57–63], Multi3D Electrifi [83–86], Amolen [51], and BlackMagic Flexible TPU [64]. Additionally, there were some obsolete or discontinued filaments that were used, such as Palmiga PI-ETPU 85-700+, 3D-Prima conductive ABS, and 3DEdge ABS. Flashforge Creator Pro [87] is the most popular 3D printer; however, some projects upgraded the extruder of this printer, especially when used with a flexible filament, such as Palmiga PI-ETPU 95-250. The second most used printer was Ultimaker 3; however, its manufacturer stopped producing this printer and a newer version is currently available (Ultimaker S3) [88]. Other articles used a wide range of 3D printers.

Figure 1 displays printed samples for the conductive filaments and Figure 2 shows the resulting physical defects in these samples. Proto-Pasta and Filoalfa Alfaohm samples are very accurate except for minor defects on the top plates and a curved surface on the contact side with printer build plate of the square sample (about four layers were curved). These curved layers usually occurred during the process of removing the finished printed samples from build plate and it is usually a user-related error resulting from using excessive force to remove the finished printed part. The samples of Palmiga PI-ETPU 95-250 resulted in some spaces between layers, especially in the corners. Conductive Filaflex samples showed some obvious errors on the top layers (especially in the cylinder sample) and extended layers (layers length exceeded the required length) on the contact side with printer build plate. Multi3D Electrifi is clearly the least accurate sample in the group with a large defect on one side, curved surfaces along the sample, and some irregular lines. Multi3D Electrifi is unique metal–polymer composite comprising a biodegradable polyester doped with cooper filament, which makes it harder to print than other conductive filaments and, as a result, long and cylinder models could not be printed with this filament (the filament sometimes bent and clogged inside the extruder). Sunlu ABS samples have a slightly extended area on the contact side with printer build plate and small defects on the top side. Amolen samples had some spaces between layers, especially in the corners; small defects on the top side; and extended layers on the contact side. 3dkonductive samples resulted in defects on all sides, especially in the long sample, and a slightly extended area in the contact side for all samples.

Table 3 listed the measured resistances of the 3D printed samples. Among the PLA-based filaments, Proto-Pasta and Filoalfa Alfaohm produced samples with lower resistance values than Amolen and 3dkonductive. On the other hand, TPU-based filaments resulted in Conductive Filaflex having lower resistance than Palmiga PI-ETPU 95-250. However, Palmiga PI-ETPU 95-250 is the most popular flexible filament, according to Table 4, and is more flexible than Conductive Filaflex. Considering the resistant values of all printed filaments, Multi3D Electrifi produced the lowest resistance values while Sunlu ABS clearly has the highest resistance values. A simplified method was used to measure the resistance, as described in Section 2.2.3. This method seems sufficient given the structural inhomogeneities of the samples. Even though the values of the measured resistance are not very accurate, these values could be used to relatively compare different filaments, as some filaments in the general produced samples had lower resistance than others.

Unfortunately, this study could not test all commercially available filaments. One of the most popular graphene-doped filaments (Black Magic Graphene) was out of stock during the time frame of this study. Additionally, there were some filaments not mentioned on Table 1, as some filaments do not have enough information describing their properties, manufacturers, or international distributors.

5. Conclusions

This study is very important for future researchers who would like to explore and use commercially conductive filaments. The 3D printing of conductive FDM filaments is a newly developed area and will probably be explored more, especially regarding medical applications, as these filaments open the door to many solutions.

To summarize, this paper examined the printed samples of eight commercially conductive filaments. These printed samples were compared by their measured resistance and physical appearance. Additionally, this paper reviewed articles that used commercially conductive FDM filaments into medical applications. These articles were collected and summarized in terms of the name of filaments used, main and specific functions of the printed conductive 3D object, and the name of the printer used to print these objects. In conclusion, the main purpose of this project was to facilitate the work of the medical researcher who would like to use commercially available conductive FDM filaments.

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