Additive manufacturing of medical instruments

A state-of-the-art review

Culmone, Costanza; Smit, Gerwin; Breedveld, Paul

DOI
10.1016/j.addma.2019.03.015

Publication date
2019

Document Version
Final published version

Published in
Additive Manufacturing

Citation (APA)
Culmone, C., Smit, G., & Breedveld, P. (2019). Additive manufacturing of medical instruments: A state-of-the-art review. *Additive Manufacturing* , *27*, 461-473. https://doi.org/10.1016/j.addma.2019.03.015

Additive Manufacturing 27 (2019) 461–473

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Review

Additive manufacturing of medical instruments: A state-of-the-art review

Costanza Culmone*, Gerwin Smit, Paul Breedveld

Bio-Inspired Technology Group (BITE), Department BioMechanical Engineering, Faculty of Mechanical, Maritime, and Materials Engineering, Delft University of Technology, the Netherlands

ARTICLE INFO

Keywords:
Additive manufacturing
3D printing
Medical device
Medical instrument
Review

ABSTRACT

Goal: Additive manufacturing, also known as 3D printing, has begun to play a significant role in the field of medical devices. This review aims to provide a comprehensive overview and classification of additively manufactured medical instruments for diagnostics and surgery by identifying medical and technical aspects.
Methods: A scientific literature search on additively manufactured medical instruments was conducted using the Scopus database.
Results: We categorized the relevant articles (71) by considering the novelty of each proposed instrument and its clinical application. Then, we analyzed the relevant articles by examining the reasons behind choosing additive manufacturing technology to produce instruments for diagnostics and surgery. Possible customization (27%) and Cost-effectiveness (23%) were the main reasons expressed. Technical specifications of the additive manufacturing technology and the material used were also analyzed, and a tendency of using material extrusion technology (35% of the applications) and polymeric materials (86% of the applications) was shown.
Conclusions: Additive manufacturing is opening the door to a new approach in the production of medical devices, which allows the complexity of their designs to be pushed to the extreme. However, we found that technical limitations need to be tackled and important aspects such as sterilization or debris contamination are still not considered to be relevant factors during the design and fabrication process. Keeping in mind the challenges of such a new field, additive manufacturing technology can be considered as a great opportunity to provide easy access to healthcare in developing countries as well as an important step toward patient-specific medicine.

1. Introduction

Additive manufacturing (AM), also known as 3D printing or rapid prototyping, is rapidly changing the perspective of how medical devices have to be designed and what can be produced and prototyped. With AM technology, a computer-aided design (CAD) model can be directly transformed into a 3D object, built layer-by-layer, in a relatively short time and with low cost, avoiding the long processes of conventional fabrication methods.

This technology emerged in the 1980s and rapidly increased in importance owing to the possibility of designing tailored tools both for patient and clinician needs [1]. When the first commercial version of the 3D printer was launched in the market in 1987, applications further increased because of high reductions in the cost of printers [2]. As shown in Fig. 1, AM has been applied in a number of medical fields such as tissue engineering to design personalized scaffolds or artificial tissues and organs for transplants [3–9]; drug delivery systems [10,11]; laboratory equipment such as probes [12] and portable test tools to detect specific medical parameters such as cortisol in the saliva [13]; assistive tools such as customized cutlery to help people with chronic diseases in their daily life [14]; orthoses and prostheses for developing countries, where the population cannot afford expensive devices [15–17]; implants [18–20]; anatomical models for both surgical planning and procedure training particularly in cases of rare pathologies [21–23]; surgical guides for screw insertions [24]; and in recent years, medical instruments for diagnostics and surgery.

In 2017, the Food and Drug Administration (FDA) published the first version of guidelines for AM of medical instruments [25]. However, to the authors' knowledge, neither an overview of the currently existing 3D-printed instruments for diagnostics and surgery nor an analysis of their common characteristics exists.

In this review, we provide a complete overview of the current state of the art in the AM of medical instruments used for diagnostics and surgery. We categorize the instruments considering the application as well as the reasons related to the use of the applied 3D printing method.

---

* Corresponding author.
E-mail addresses: c.culmone@tudelft.nl (C. Culmone), g.smit@tudelft.nl (G. Smit), p.breedveld@tudelft.nl (P. Breedveld).

https://doi.org/10.1016/j.addma.2019.03.015
Received 31 October 2018; Received in revised form 27 February 2019; Accepted 17 March 2019

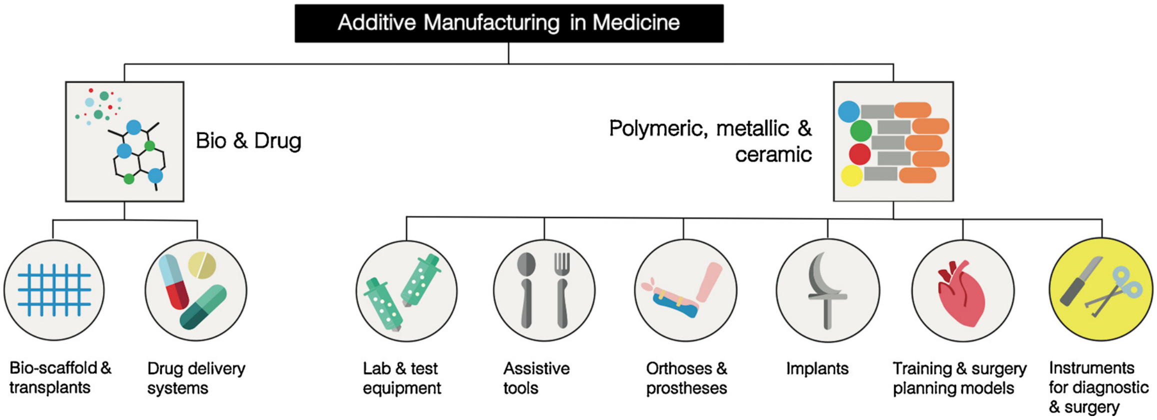

Fig. 1. Classification of medical fields related to additive manufacturing. The first level of classification concerns the material used and the second level the medical field of application. This review paper focuses on instruments for diagnostic and surgery (highlighted in yellow) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

2. Literature search methods

2.1. Scientific literature research

A scientific literature search was conducted using the Scopus database on the AM of medical instruments used for diagnostics and surgery. The choice for Scopus database rather than other databases, such as Web of Science or PubMed, is due to its completeness in journal titles, the possibility of using nested Boolean searches, and its classification of articles in multiple subject areas which allows achieving a wider range of articles [26]. The search keywords of the query were organized into three categories: (1) fabrication technology (*3D print*, additive manufactur*, rapid prototyp**), (2) product class (*instrument, tool, prototype, device, appliance, equipment*), and (3) application area (*med*, surg*, diagnos**). We decided to use only general terms in all categories to have a broader search query and we excluded specific terms such as the specific AM technologies, specific types of instruments, and specific names of interventions. We did not limit the search to a particular period; however, we decided to crop the result to include only the English articles in the subject area of “Engineering” and “Medicine.” We searched in titles, abstracts, and keywords of the documents. Our complete search query was TITLE-ABS-KEY (("3D print*" OR "additive manufactur*" OR "rapid* prototyp*") AND (instrument OR tool OR prototype OR device OR appliance OR equipment) AND (med* OR surg* OR diagnos*)) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "MEDI")) AND (LIMIT-TO (LANGUAGE, "English")).

2.2. Eligibility criteria

In this review, we define a medical instrument as a tool for examining or treating patients. The tool must be directly in contact with the patient but is not meant to stay into the body for more than the duration of the examination or treatment. Considering the three categories used for the search keywords, in Category (1), “fabrication technology,” we considered the seven main categories of AM technologies defined by the Standard Terminology for AM Technologies (ASTM): binder jetting, direct energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization [27]. Bioprinting and drug printing were excluded. In Category (2), “product class,” we included surgical instruments used inside the body, as well as diagnostic instruments used to examine the patient from the outside. Because we focused on medical instrumentation, we excluded surgical guides developed for navigation during surgery, as well as 3D-printed anatomic models for surgical planning and training, implants, prostheses, orthoses, probes, and drug portable devices. In Category (3), “application area,” we considered eligible all the instruments used in the medical domain except for laboratory tools that are not directly in contact with the patient.

2.3. Literature search results

The search resulted in 2616 scientific articles, the titles and abstracts of which were scanned. We selected 53 articles that fulfilled the eligibility criteria. Besides analyzing the results obtained with the search query, we also checked the references of the selected articles to include the ones not captured by the query. We found 18 additional articles, resulting in 71 total articles. The obtained information was analyzed from different perspectives. First, we considered the clinical application and the novelty of the devices. Then, we reviewed the articles on the reason for using the AM technology. Finally, technical information related to the AM technology used in the field of medical instruments was retrieved.

3. Clinical application and novelty of AM devices

We categorized the instruments considering their novelty and clinical application (Fig. 2). We considered a device to be a “conventional instrument” when its basic design was based on traditional instruments used in diagnostics and surgery such as surgical tweezers. A completely new design was, instead, categorized as an “unconventional instrument.” Each of these categories was further split into two subcategories considering the clinical application. We defined a device designed for diagnostic or surgical approaches that could be used in different types of procedures as a “general purpose instrument.” Laparoscopic or endoscopic generic instruments fall into this category. On the contrary, we defined a device designed for only one particular type of surgery as a “specific-purpose instrument,” for example, polyps dissection in the colon (Fig. 2). Articles in which a conventional instrument is proposed are grouped in Table 1 and those that propose an unconventional instrument are listed in Table 2.

3.1. Conventional general-purpose instruments

A straightforward use of AM is to try and produce medical instruments that are identical to those manufactured by conventional methods, such as molding or machining. General surgical kits were presented by George et al. [28], Wong et al. [29,30], Ibrahim et al. [31], and Kondor et al. [32]. Surgical kits are generally composed of tweezers, needle drivers, hemostats, retractors, forceps, and scalpels and are designed to perform relatively common surgical procedures (Fig. 3a).

Other research groups focused only on one such instrument with

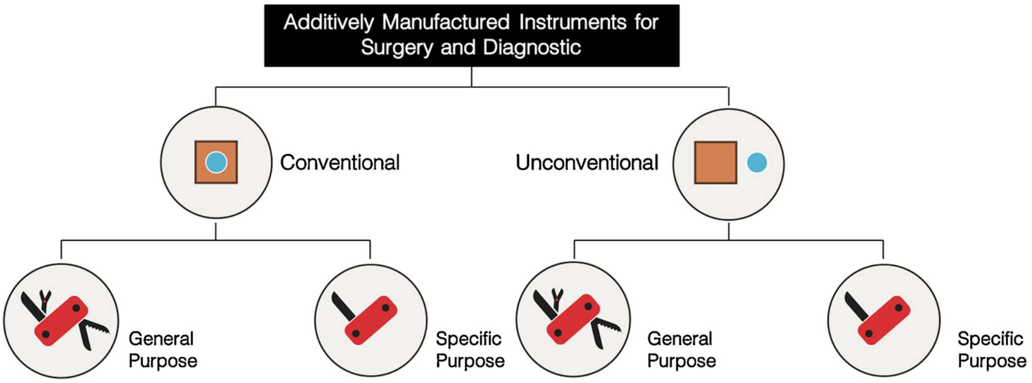

Fig. 2. Classification of additively manufactured medical instruments for diagnostics and surgery.

[32,34–39] or without [40–42] changes in its design. While Singh et al. [40] presented a fully assembled microsurgery tweezer, Paraskevopoulos [34] introduced a modified burr hole: a device used in intracranial procedures as the entry port to stabilize a range of endoscopic instruments (Fig. 3b). The modified design of this device is meant to allow for solo surgeries. The approach used by Băilă et al. [43,44] was different; they printed a general-purpose dental elevator that was manufactured in two pieces with two different AM technologies: vat photopolymerization for the handle and power bed fusion for the beak. The choice of printing only a part of an instrument was made also by Sanchez-Tamayo et al. [45], who tried to manufacture grippers and cutting tools for integration into surgical robots. An AM diagnostic device was presented by Aguilera-Astudillo et al. [46], who designed a stethoscope in which the chest piece was manufactured using a 3D printer.

3.2. Conventional specific-purpose instruments

An interesting approach to AM is to use the 3D printing process to partly modify the design of conventional instruments to perform specific procedures. The changes made to the design are mostly related to the functionality [47,49–51,54] or size [48,53,55,57,58]. An example of functionality change is given by the reciprocating syringe of Rothenberg et al. [47] for image-guided aspiration, as shown in Fig. 4a. In a conventional syringe, sucking small parts of solid organs or fluids while maintaining the vacuum often needs the help of an assistant. The reciprocating syringe uses a double lumen structure allowing the physician to perform a solo procedure by inverting the movement of the syringe plunger. A modification of the conventional equipment for specific ventilation imaging, which is a technique used to measure the air distribution in the lungs, was performed by Cook et al. [54]. They proposed an alternative bypass flow attachment that was completely manufactured using 3D printing technology and could substitute a

Table 1
Author(s), year of publication, clinical application, and corresponding category in the classification of relevant articles for conventional medical instruments.

Author(s)	Publication year	Clinical Application	Classification
George et al. [28,33]	2017	General surgery	C-GP
Paraskevopoulos [34]	2016	Intracranial surgery	C-GP
Singh et al. [40]	2016	Microsurgery	C-GP
del Junco et al. [35]	2015	Endoscopic and laparoscopic equipment	C-GP
Rankin et al. [41]	2014	Open surgery	C-GP
Wong and Pfahnl [29]	2014	General surgery	C-GP
Wong [30]	2015	General surgery	C-GP
Yamamoto et al. [36]	2015	General surgery	C-GP
Ibrahim et al. [31]	2015	General surgery	C-GP
Kondor et al. [37]	2013	General surgery	C-GP
Kondor et al. [32]	2013	General surgery	C-GP
Fuller et al. [38]	2014	Bone reduction	C-GP
Băilă et al. [44]	2016	General surgery	C-GP
Băilă et al. [43]	2016	Dental procedure	C-GP
Kaleev et al. [42]	2017	General surgery	C-GP
Sanchez-Tamayo and Wachs [45]	2018	Robotic surgery	C-GP
Aguilera-Astudillo et al. [46]	2016	Diagnostics	C-GP
Yamamoto et al. [39]	2018	Endoscopic surgery	C-GP
Rothenberg et al. [47]	2017	Ultrasound-guided aspiration	C-SP
Gálvez et al. [48]	2016	Assisted ventilation	C-SP
Way et al. [49]	2015	Assisted ventilation	C-SP
Kontio et al. [50]	2012	Mandible fracture correction	C-SP
Way [51]	2018	Flow rate control	C-SP
Walter et al. [52]	2017	Polyp dissection in colonoscopy	C-SP
Navajas and Hove [53]	2017	Transconjunctival vitrectomy	C-SP
Cook et al. [54]	2015	Specific Ventilation Imaging	C-SP
del Junco et al. [55]	2015	Urine flow kidney-bladder	C-SP
Ko et al. [56]	2016	Mucosal/submucosal dissection	C-SP
Walker et al. [57]	2016	Breast Brachytherapy	C-SP
Ulmeanu et al. [58]	2016	Tracheostomy	C-SP
Steinemann et al. [59]	2018	Distal esophageal mucosectomy	C-SP

Conventional General Purpose (C-GP); Conventional Specific Purpose (C-SP).

Table 2
Author(s), year of publication, clinical application, and corresponding category in the classification of relevant articles for unconventional medical instruments.

Author(s)	Publication year	Clinical Application	Classification
Morimoto and Okamura [71]	2016	Minimally invasive procedure	U-GP
Oliver-Butler et al. [67]	2017	Endoscopic procedure	U-GP
Jelínek et al. [60]	2014	Minimally invasive surgery	U-GP
Jelínek et al. [61]	2015	Minimally invasive surgery	U-GP
Jelínek et Breedveld [62]	2015	Minimally invasive surgery	U-GP
Qi et al. [72]	2016	Minimally invasive surgery	U-GP
Amanov et al. [73]	2015	Minimally invasive surgery	U-GP
Boehler et al. [79]	2016	MR-guided percutaneous procedure	U-GP
Entsfellner et al. [80]	2014	Ear Nose Throat (ENT) surgery	U-GP
Krieger et al. [76]	2017	Endoscopic surgery	U-GP
Mintenbeck et al. [68]	2014	Minimally invasive surgery	U-GP
Cortes-Rodicio et al. [81]	2017	PET-guided biopsy	U-GP
Seneci et al. [63]	2015	Laparoscopic surgery	U-GP
Coemert et al. [78]	2017	Minimally invasive surgery	U-GP
Nowell et al. [74]	2017	Endonasal surgery	U-GP
Roppenecker et al. [70]	2013	Single-port gastroenterology surgery	U-GP
Kesner and Howe [83]	2011	Force measurement in catheter	U-GP
Roppenecker et al. [77]	2012	Single port surgery	U-GP
Seneci et al. [64]	2017	General surgery	U-GP
Schmitz et al. [75]	2017	General surgery	U-GP
Sakes et al. [65]	2018	Minimally invasive surgery	U-GP
Sahlabadi et al. [66]	2017	Percutaneous intervention	U-GP
Fontanelli et al. [84]	2017	Minimally invasive robotic surgery	U-GP
Kim et al. [69]	2015	Neurosurgery	U-GP
García et al. [85]	2018	Trans-anal endoscopic procedure	U-GP
Saafi et al. [82]	2018	Laparoscopic surgery	U-GP
Zizer et al. [86]	2016	Endoscopic submucosal dissection	U-SP
Chen et al. [87]	2016	Cervical intraepithelial neoplasia	U-SP
Krieger et al. [88]	2016	Partial nephrectomy	U-SP
Epaminonda et al. [89]	2016	Cervical cancer	U-SP
Menikou et al. [90]	2017	Pain palliation bone cancer	U-SP
Peikari et al. [91]	2011	Transrectal brachytherapy	U-SP
Maeda et al. [92]	2015	Endoscopic submucosal dissection	U-SP
Traeger et al. [93]	2014	Endoscopic submucosal dissection	U-SP
Yiallouras et al. [94]	2014	Prostate cancer	U-SP
Roppenecker et al. [95]	2012	Endoscopic submucosal dissection	U-SP
Rugg et al. [96]	2016	Scanning fiber endoscope (SFE)	U-SP
Myloas and Damianou [97]	2014	Brain cancer	U-SP
Dikici et al. [98]	2018	Hysterectomy	U-SP

Unconventional General-Purpose (U-GP); Unconventional Specific-Purpose (U-SP).

significant number of components with only one part.

Navajas and Hove [53] provided an example of size change using 3D printing in the fabrication of a trocar-cannula for transconjunctival vitrectomy, a procedure during which the gel-like material in the eye is substituted by a saline solution. In this case, the functionality of the trocar-cannula is not changed, but because of the 3D printing technology, the size can be customized considering the surgical instrumentations used during the procedure. A similar approach was taken by Walker et al. [57] in designing measuring tools to estimate the size of a probe used in lumpectomy, a breast cancer removal procedure (Fig. 4b). The overall design of the measuring tools, a handle with a sphere on top, is the same as that of the probe. However, by using AM, the size of the sphere can be changed to diameters ranging from 1.5 to 5 cm depending on the patient's needs. In this way, an appropriate probe can be chosen by avoiding unnecessary sterilization of probes of the wrong size.

Furthermore, AM can be used to fabricate additional parts for standard devices or procedures. Walter et al. [52] presented a cap that can be added to a conventional colonoscope to enhance the field of view of the instrument and detect the presence of polyps in the colon. Using AM allowed the size of the cup for different colonoscopes to be customized. Ko et al. [56] also printed a set of caps (Fig. 4c). The caps

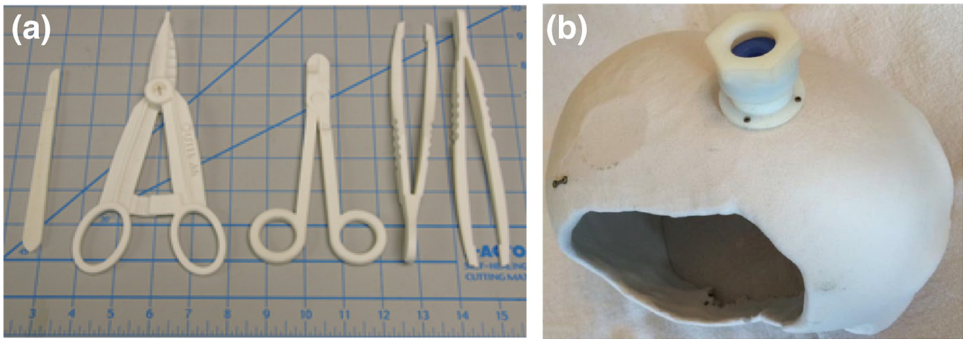

Fig. 3. Examples of "conventional general-purpose" instruments: (a) surgical kit: scalpel, hemostat, needle driver, and forceps [33]; (b) modified burr hole presented by Paraskevopoulos [34].

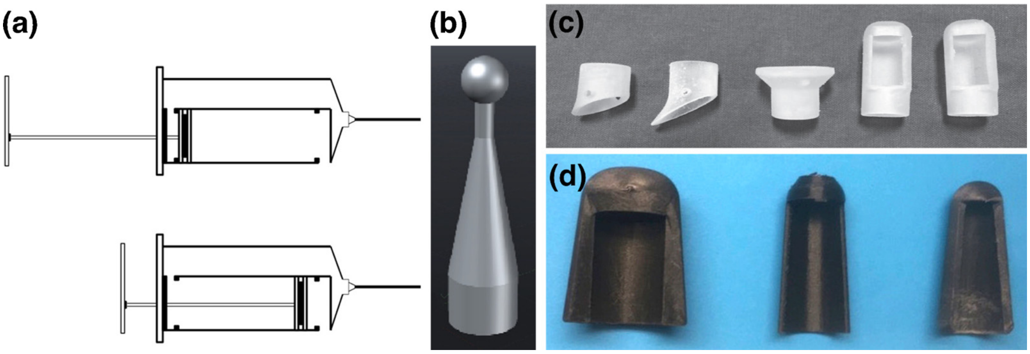

Fig. 4. Examples of "conventional specific-purpose" instruments: (a) sketch of reciprocating syringe by Rothenberg et al. [47]; (b) CAD of measuring tool designed by Walker et al. to choose the appropriate probe for lumpectomy procedure [57]; (c) caps designed to be added to a conventional gastroscope to perform different types of biopsies [56]; (d) retractors for distal esophageal mucosectomy [59].

were added to a conventional gastroscope and the shape was varied depending on the procedure to be performed. For example, a cap with a wide end was used to perform esophageal biopsies—removal of a small piece of tissue. Fig. 4d shows a space holder proposed by Steinemann et al. [59], which was used to better expose the esophagus wall during the suturing phase of mucosectomy, a partial resection of the bowel wall, and enhance the final result.

3.3. Unconventional general-purpose instruments

AM has opened the doors to create new designs for medical instruments, some of which are impossible to manufacture by conventional methods. These instruments are generally designed for minimally invasive surgical procedures, during which one of the most important aspects is the maneuverability of the instrument inside the human body.

AM technology can be used to fabricate steerable surgical instruments [60–66]. The DragonFlex is a new concept of a laparoscopic grasper, fully 3D printed with seven degrees of freedom (DOFs), to give the surgeon the possibility to steer the instrument inside a patient's body [60] (Fig. 5a). A smart steerable needle was presented by Sahlabadi et al. [66], in which the shaft was 3D printed and guided by nitinol wires.

Many research groups focused their work on new designs for continuum robots and manipulators [67–69,71–75]. Morimoto et al. [71], Oliver-Butler et al. [67], and Amanov et al. [73] proposed concentric tube structures based on the sliding motion of one tube into the other to achieve a snake-like motion (Fig. 5b). In these concentric tube structures, the number of elements is usually kept to a minimal, and the 3D printing material and design properties are used to increase the steerability. The same principle was used by Kim et al. [69] to implement a snake-like system made of three segments fully assembled (Fig. 5d). A similar continuum robot was presented by Mintenbeck et al. [68] but, in contrast to concentric tube structures that usually decrease the number of parts, the body of this robot was made of multiple elements that were grouped into two cable-driven segments able to move with four DOFs, as shown in Fig. 5c. The research group led by Professor Lueth [76] proposed a branched overtube system to be used in combination with conventional endoscopes and endoscopic instruments. The system was fully 3D printed and the control was purely mechanical. They presented different structures for the overtube system and the configuration of the branched unit, as well as different materials that can be used for the production of the device [70,77,78] (Fig. 5e).

Other interesting examples of "unconventional general-purpose" medical instruments concern positioning and stabilizing systems [79–82], such as the one designed by Boehler et al. [79]. The stabilizing system is able to modulate the needle insertion for biopsy intervention by estimating the patient's movements related to the breathing cycle. In this case, AM allows the system to be magnetic resonance imaging (MRI)-compatible.

Force sensors manufactured using AM are also part of this category, owing to the novelty in their design, which aims to directly integrate the sensor into a catheter [83], or a trocar [84] in one printing step. Finally, García et al. [85] presented a new 3D-printed device to perform trans-anal endoscopic surgical procedures that is able to provide an adequate workspace without inflating the rectum. In this case, AM allows the device to be modified according to the patient's needs.

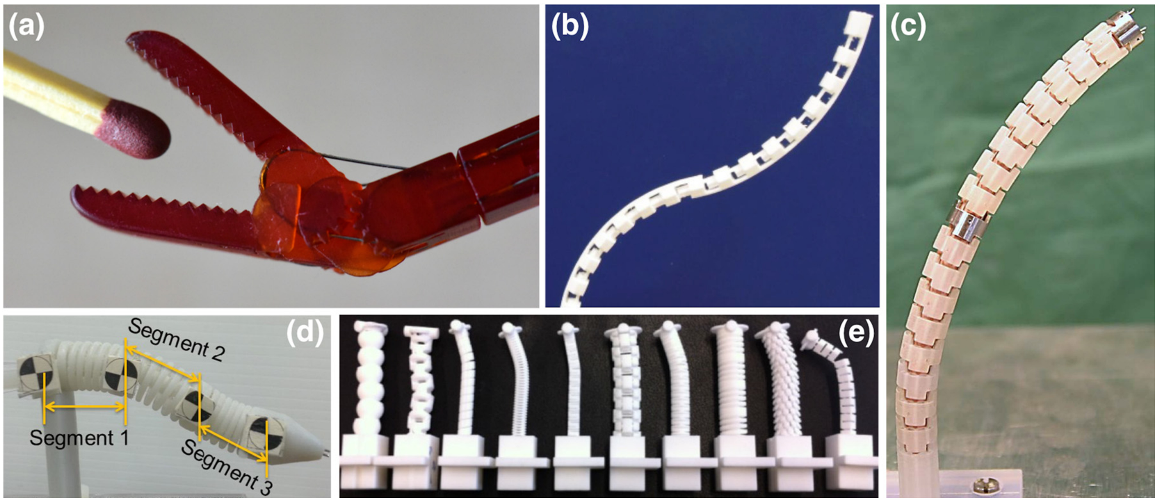

Fig. 5. Examples of "unconventional general purpose" instruments: (a) steerable laparoscopic grasper with seven degrees of freedom; (b) 3D printed concentric tube robot [67]; (c) cable-driven continuum robot [68]; (d) the snake-like system presented by Kim et al. [69]; (e) different structures of the overtube presented by professor Lueth's group [70].

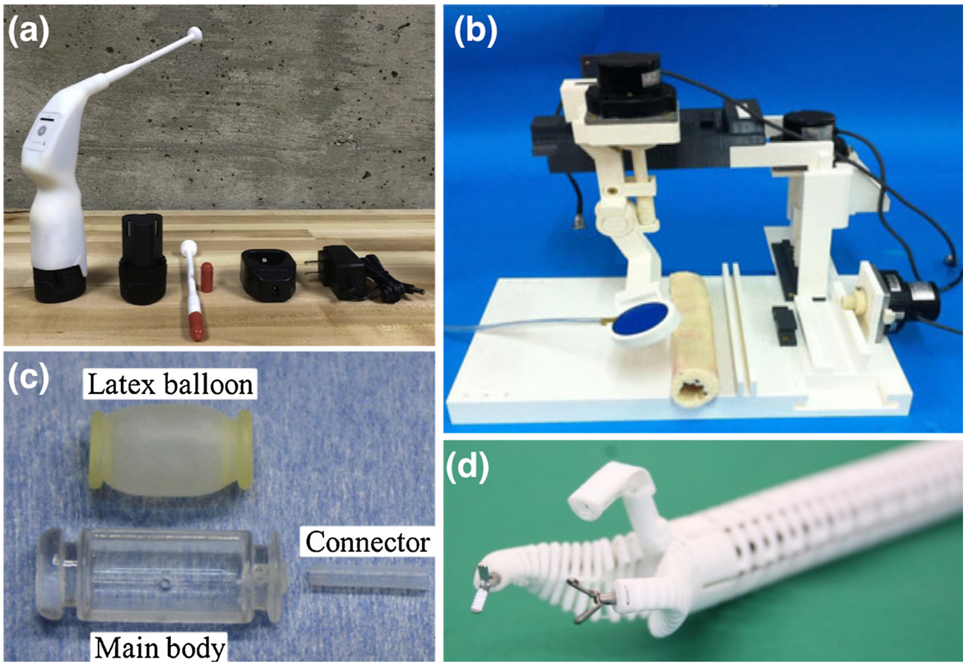

Fig. 6. Examples of “unconventional specific-purpose” instruments: (a) thermo-coagulator to treat a type of gynecological cancer [87]; (b) MRI-compatible device for pain palliation in bone cancer [90]; (c) device to implant cell sheets [92]; (c) detail of the branched end of the overtube system proposed by Professor Lueth’s group [93].

3.4. *Unconventional specific-purpose instruments*

The “unconventional specific-purpose” category clusters works in which the authors identified a specific procedure or disease, and used the AM technology to design an innovative instrument. Five of the found articles presented instruments to treat or provide palliative care for different types of cancer [87,89,90,94,97]. Chen et al. [87] introduced a new inexpensive thermo-coagulator to treat cervical neoplasia, an anomalous growth of cells in the female cervix (Fig. 6a) while Menikou et al. [90] proposed an MRI-compatible device for pain palliation in bone cancer using thermal ablation (Fig. 6b). A 3D-printed device for brachytherapy, a treatment via rectum in which radioactive sources are placed directly in contact with the area of interest was proposed by Peikari et al. [91]. A new device was also proposed by Dikici et al. [98] to perform a particular gynecological surgery during which the uterus is removed with a laparoscopic approach. The AM technology was used by Rugg et al. [96] to fabricate a tailored handpiece to hold the scanning fiber endoscope, a particular instrument used to acquire dental images without using X-ray.

Fig. 6c shows an interesting application for the implantation of cell sheets. Maeda et al. [92] proposed a device to implant cell sheets after the removal of gastrointestinal tumors in which the cell-sheet carrier was 3D printed. Finally, the branched overtube system presented by Professor Lueth’s group was modified, in order to be suitable for a specific surgery during which a gastrointestinal tumor was removed [86,93,95] (Fig. 6d). The overtube system was tested in the laparoscopic environment as well to remove small kidney tumors [88].

4. Reasons for design of AM devices

Conventional manufacturing technologies are widely known and people have significant knowledge on the possibilities and limits of such technologies. Thus, it is interesting to analyze the reasons why AM technology was used to produce the medical instruments found in the literature. In Fig. 7, we highlighted eight reasons for the choice of AM expressed in the articles, which if not explicitly expressed by the authors were found on a careful analysis conducted by the authors of this review. Multiple reasons are often mentioned in the same article.

4.1. *Customization*

One of the main reasons expressed in the articles (27%) is the possibility of customization. Customization can concern patients, in which case instruments are customized in their dimension or design not only to meet the patient’s anatomy, but also the clinician’s needs for more intuitive ergonomics and user-friendliness [41]. The surgical kit presented by Kondor et al. [32] is an example; it was designed to be modified according to the needs of the patient or the surgeon. Customization of the instrumentation can also be performed considering the procedure. The instrument can then change in its size for adaptation to conventional devices, such as colonoscopes or endoscopes [52,56] (Fig. 4c) or considering the specific size of the tumor [88].

4.2. *Cost-effectiveness and disposability*

Many articles (31) justified the choice for AM owing to a considerable reduction in production cost. Ten of these articles estimated the incurred cost. Some of them considered only the price of the material [41,48,54,96], some others carried out a complete evaluation of the expenses considering the material, cost of printer, payment of an expert for the design process, duration of printing, and post-processing [58]. Walker et al. emphasized the advantage of using the AM technology to avoid unnecessary sterilization cycles of ultrasounds probes [57]. The probe has a lifespan of 100 sterilizations. Therefore, avoiding unnecessary sterilization of the probes using measuring 3D printed tools decreases the cost of the entire procedure (Fig. 4b). Directly connected with the cost-effectiveness and customization is the possibility of making disposable instruments. AM offers a low-cost production method, allowing customization on-demand of the instruments for patient-specific procedures [35,88].

4.3. *Accessibility*

Eight articles emphasized the importance of AM in terms of accessibility: the possibility of having access to healthcare in remote areas. Developing countries, military expeditions, and space missions are the main scenarios proposed. The opportunity is related not only to the low costs of the AM technology [31,41,87] but also to the possibility of providing an open-source library in which the basic design of

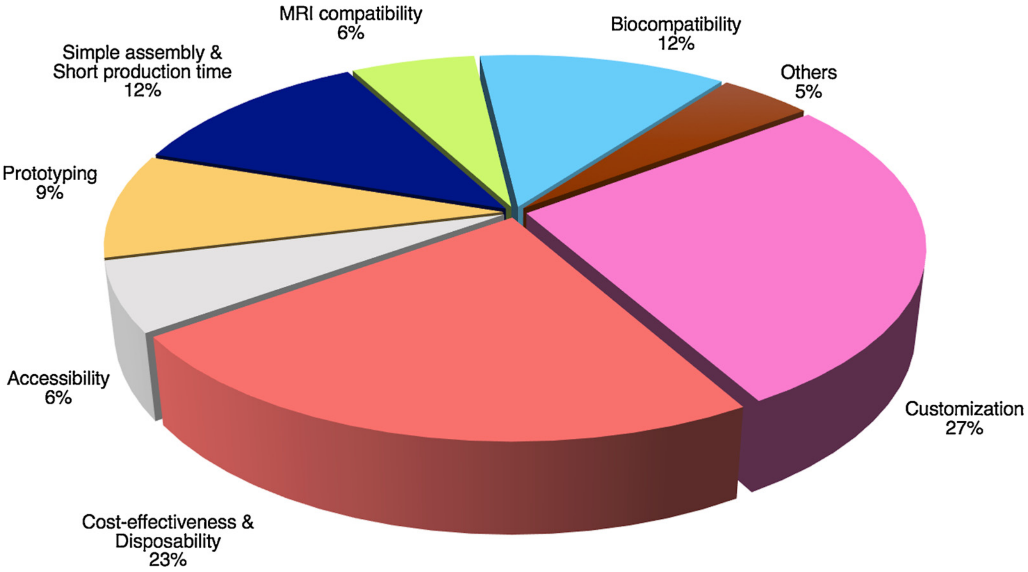

Fig. 7. Various reasons related to the choice of using additive manufacturing to print medical instruments for diagnostics and surgery.

instruments is uploaded and offered for free [32].

4.4. Simple assembly and short production time

AM is categorized as a rapid prototyping technology as it offers a more rapid fabrication process compared to conventional manufacturing. In a number of articles (16), the reason for choosing AM is related to the necessity of having a quick turnaround during the design process. An additional advantage of AM is that the production and assembly time do not increase with the complexity of the design, allowing a reduction in the number of components while increasing the complexity of a single element [63,93]. As a result, the design evaluation as well as the optimization phase can be carried out in a shorter time [49].

4.5. MRI-compatibility and biocompatibility

Depending on the medical application, an important aspect is the MRI-compatibility of the device proposed. A significant number of articles (8) highlighted the advantage of AM in fabricating instruments with material properties compatible with MRIs. Another fundamental property that is taken into consideration in various articles (16) is the biocompatibility of the medical instrument. Biocompatibility is mainly related to the material used. There are two main polymers used in the reviewed articles, where their use is justified by their biocompatibility; polylactic acid (PLA) is described in three articles, and PA2200, a type of polyamide is described in six articles. Metals such as stainless steel, alumina–zirconia composites, or cobalt–chromium alloys are also used to fabricate medical instruments owing to their biocompatibility but their use is limited compared to that of polymeric-based materials.

4.6. Prototyping and others

When conventional manufacturing methods are used in the first phases of a design process, the time required for the production of a prototype can be extremely long. The tuning phase to optimize and ameliorate the functionality of the design can be even longer. For this reason, in many articles (12) AM was used to fabricate the first prototype as a proof-of-concept [81,82,98]. Often, the 3D-printed prototype was used to test the design properties, by using the actual size of the device [84] or by giving it larger dimensions [74]. In a few articles (6), the reason behind the choice for AM is more related to material properties [44] or particular design configurations that are difficult to fabricate [78].

5. Technology to manufacture AM devices

5.1. AM technologies

The term “additive manufacturing” groups a large number of technologies. Owing to its novelty, many types of classifications can be found in the literature. In this review, we used the categorization given by the ASTM organization, which provides seven well-defined groups of AM technologies [27]. Fig. 8 shows the percentages related to the use of these technologies to manufacture medical instruments. Clearly, the most applied technology is material extrusion (ME) with 35% of the applications. The ME technology is based on the extrusion and deposition of thermoplastic material through a nozzle. The semi-melted material in contact with the low-temperature platform rapidly hardens and solidifies keeping the 3D shape. ME includes fused deposition modeling (FDM), which is the cheapest process currently available in the market [99].

Powder bed fusion (PBF) uses energy from laser or electron beam to melt layer by layer particles together, while in material jetting (MJ) drops of liquid material are deposited on a platform and cured with UV light every layer. PBF together with MJ are widely used (26% and 21%, respectively), while vat photopolymerization (VP) is used only in nine cases (11%). In VP a vat of liquid photopolymer is selectively exposed

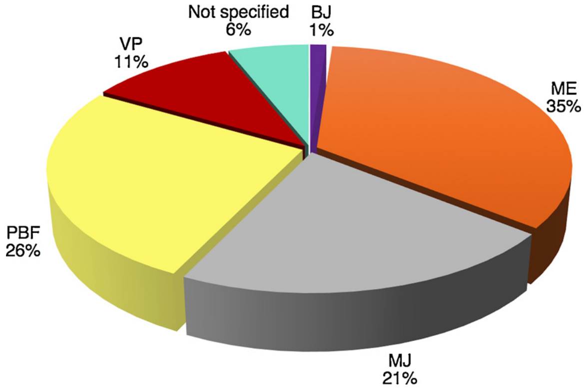

Fig. 8. Various additive manufacturing technologies used to print medical instruments (see text for abbreviations). Direct energy deposition (DED) and sheet lamination (SL) are not presented in the chart because no articles were found using these technologies. The percentages are calculated considering the number of applications that can be multiple in the same article.

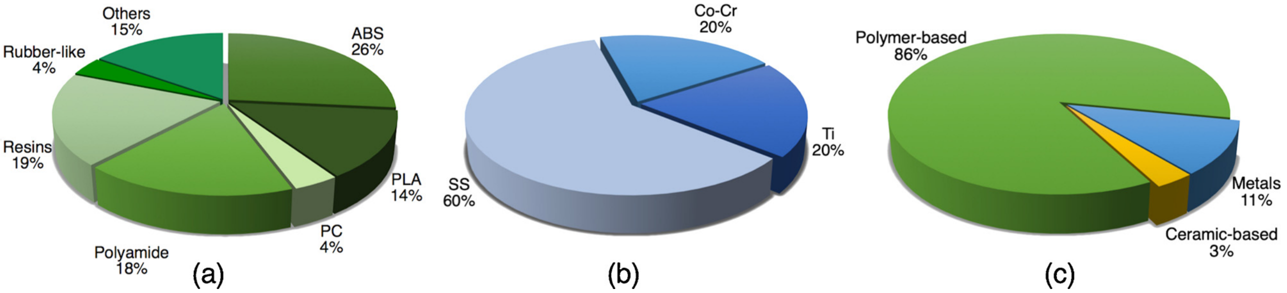

Fig. 9. (a) Percentages of different polymeric-based materials used to print medical instruments (see text for abbreviations); (b) percentages of different metallic materials used to print medical instruments; (c) percentages of different categories of materials used to print medical instruments.

to a laser beam which polymerized layer by layer the material to create solid parts. VP includes techniques such as stereolithography (SLA) and digital light process (DLP). Ulmeanu et al. [58] presented the only application of binder jetting technology (BJ) in the production of medical instruments. BJ uses liquid bonding agent on powder material to build 3D structures layer by layer.

Direct energy deposition (DED) uses energy to directly melt the material while is deposited on the platform, while sheet lamination (SL) stacks and laminates sheets of material using processes such as ultrasonic welding. In the literature analyzed for this review, both DED and SL were not used to produce medical instruments; this could be owing to the limitation in material choice. Five of the articles did not mention the specific technology applied but only the material.

5.2. AM materials

The choice of materials is directly related to the technology used. We decided to divide the materials into three main categories: polymer-based, metals, and ceramic-based. The group with the largest number of applications (86%) is that of polymer-based materials (Fig. 9c). This is in line with the analysis of the technologies presented in the previous section in which only PBF and BJ allow the use of metals and ceramic-based materials. Polymer-based materials include acrylonitrile butadiene styrene (ABS), which is used in 21 different applications, PLA, polyamides (nylon), polycarbonates (PC), resins, and rubber-like materials. When not specified, the material category (polymer-based) was deduced from the technology applied owing to the direct correlation between the material and type of printer used and categorized as “others.” There was a single application with polycaprolactone (PLC), which was included into “others” [73] (Fig. 9a). The large use of polymer-based materials is partially related to biocompatibility, as for PLA, and biodegradability as for PA2200 polyamides raw powder (certificated as biocompatible according to EN ISO 10993-1) [88].

Compared to polymer-based materials, metals are rarely used; they are applied only in 12% of the cases (11 applications). Stainless steel (SS) is most commonly used (6 applications), while both titanium (Ti) alloy cobalt–chromium (Co–Cr) alloy are each applied in two cases (Fig. 9b). We found the use of ceramic materials in three applications: ceramic-filled epoxy resin and alumina-zirconia composite in the DragonFlex steerable laparoscopic grasping forceps of Jelínek et al. [60,62] and in the personalized tools for tracheostomy, a surgical procedure to help the breathing, by Ulmeanu et al. [58].

6. Discussion

In this review, we provided an overview of the AM of medical instruments for diagnostics and surgery found in the literature, considering the novelty and clinical application. We analyzed the reasons related to the choice of using AM, the technologies, and the materials used. In this section, we will focus on properties and performance, the medical regulations and sterilization of additively manufactured medical instruments, the production cost, and the use of this technology to expand healthcare in developing countries, as well as to allow new surgical procedures.

6.1. Properties and performance of AM devices

Widely accepted advantages related to the use of AM are the simplicity of the manufacturing phase and the possibility of making complex shapes without increasing complexity in the fabrication process. However, due to the novelty of AM, there are still issues to be tackled, regardless of the specific technology. The AM processes create inhomogeneity in the material. Inhomogeneity creates anisotropic behavior of the material and can lead to unpredictable ruptures of the printed parts [71,80,84]. Another main cause of weaknesses in AM parts is print orientation [74]. Changing the orientation of printing can alter the stiffness of a printed part, as shown by Entsfellner et al. who printed a compliant mechanism in different directions [80]. Wong and Nowell et al. noticed weaknesses when forces are applied transversally to a 3D printed layer [29,74]. Print orientation can also affect the cross-section of the printed part [71], but it is not the only factor that plays an important role during the printing process. Different printers and materials with the same technology can alter the final design [71,96].

Accuracy is another important factor in AM; the higher the accuracy of the printer, the more the 3D printed device will correspond to the designed CAD model. VT is most accurate, but limitations in material choice limit its use in the medical field [62]. PBF is less accurate than VT, causing changes in design properties such as decreased flexibility of thin structures due to increased thickness of the layers [78]. Despite this, PBF offers the possibility to print without any support material due to the powder bed that creates support itself [71]. MJ allows the use of materials with properties ranging from high stiffness to great flexibility. Nevertheless, it is necessary to remove a considerable amount of support material with consequences on the surface properties of the printed part [62]. ME is the most used AM technology due to its simplicity and the availability of cheap printers. However, ME needs support material [57], a controlled extrusion temperature and specific nozzle size depending on the material used [73]. It is therefore clear that, regardless the specific AM technology, the CAD model must be modified considering limitations and accuracy of the printer [35,58,53,71], but also considering the results given by printing attempts and iterations [28,62].

In Section 5.2 we pointed out that the majority of the materials used are polymer-based. Many polymers, such as PLA or nylon, are widely used in the medical field and for this reason already certificated for their biocompatible properties. However, polymers can change their properties over time. PLA becomes stiffer after some time [73] while some of the epoxy resins used in SLA change due to their photosensitivity [62]. The use of a polymer-based material also influences the mechanical properties of medical instruments. Brittleness and limitations in exerted forces [40] are reasons why AM is often considered to produce disposable instruments.

Nevertheless, there are advantages that only AM can provide. Boehler et al. presented a variable stiffness spherical joint printed using

Table 3
Examples of 3D printers available in the market for fused deposition modeling (FDM), multijet (MUJ), stereolithography (SLA), and selective laser sintering (SLS), considering a similar build volume [99,102].

Printing process (printing technology)	Name	Company	Build Volume (cmxcmxcm)	Min. thickness layer (μm)	Material	Cost (€)
FDM (ME)	Ultimaker 2	Ultimaker	23.0 × 22.5 × 20.5	20	polymeric	2,500
FDM (ME)	AW3D HDX	Airwolf 3D	30.5 × 20.3 × 30.5	60	polymeric	3,500
MUJ (MJ)	ProJet 3510 series	3D Systems	29.8 × 18.5 × 20.3	16-32	polymeric	69,500
Polyjet (MJ)	Objet Eden	Stratasys	25.5 × 20.0 × 25.2	16	polymeric	19,800
SLA (VP)	ProJet6000	3D Systems	25.0 × 25.0 × 25.0	50	polymeric	200,000
SLA (VP)	Form 2	Formlabs	14.5 × 17.5 × 14.5	25-100	polymeric	4,000
SLS (PBF)	Elite P3600	TPM	36.0 × 36.0 × 60.0	130	polymeric	150,000
SLS (PBF)	ProX series	3D Systems	38.1 × 33.0 × 46.0	100	polymeric	500,000

the multi-material properties of the MJ [79]. They printed a rigid polymer and a rubber-like material together in a single component. Roppenecker et al. printed a snake-like system designed as multiple pieces, but printed as a single structure, playing with tolerances in between the different elements [70]. Moreover, compliant mechanisms and joints can be printed [80], as well as different surface patterns [63], playing with material properties and thickness.

6.2. Medical regulations and sterilization

In 2017, the FDA issued a new guideline to share technical aspects on the use of AM technologies to fabricate medical devices [25]. The guideline covers all steps: from the design process to the test phase and sterilization. One of the critical aspects on the production of medical devices using AM is maintaining tight tolerances. Depending on the AM technology used, it can be challenging to keep the correct dimensions and geometry, especially in small-scale applications [58], and to produce identical pieces respecting tolerances. Another important factor that is almost never considered in the analyzed articles is the possibility of debris remaining even after sterilization, owing to the complex shape of the device. Any medical device needs to be sterilized before direct contact with the patient. However, the more complex the instrument geometry, the more difficult the sterilization process.

According to the Centers for Disease Control and Prevention, there are many sterilization techniques, such as autoclave, hydrogen peroxide gas plasma, and ethylene oxide gas [100]. The autoclave, which uses steam under pressure at a high temperature (121 °C or 134 °C), is nontoxic and allows quick cycles of sterilization. However, it can damage instruments printed with certain polymeric materials that have a relatively low melting point. For example, PLA becomes soft at 60 °C [54] and ABS deteriorates at 88 °C [53]. The autoclave can be used with instruments printed with the PA 2200 polymer, but in this case, sterilization can be done only one time because, after the first use, the blood contamination cannot be eliminated [78]. Ethylene oxide gas and hydrogen peroxide gas plasma are low-temperature sterilization methods (below 60 °C) with a cycle duration of 12–24 h and 28–75 min, respectively [100]. However, ethylene oxide gas may be toxic and FDA recommends to use it as a last resort [101]. Hydrogen peroxide gas plasma is safe for the body and the environment. Both ethylene oxide gas plasma and hydrogen peroxide gas plasma can be used with additively manufactured instruments, but none of the covered studies have implemented these sterilization methods.

An interesting approach is suggested by three articles [29,41,57]. Due to the high temperature with which the material is extruded using FDM, it could be possible to consider the process as self-sterilizing (if the piece is printed in a sterile platform and environment), according to the polymerase chain reaction (PCR) test for bacteria load [41]. However, only 90% of the instruments printed by Kondor et al. were considered accurately sterilized directly after the printing process [32].

The overall conclusion is that even if some studies show an interest in the sterilization phase, many of them (42 studies) do not take this aspect into consideration. The choice of using AM in the early prototyping phase can explain the lack of concern in the sterilization phase. However, owing to the connection between complexity of design and difficulties in the sterilization process, it would be preferable to consider sterilization as a priority in the development of additively manufactured medical devices.

6.3. Production cost

AM is often considered as an inexpensive method of fabrication, and if we consider only the material cost, this is indeed frequently true [48,96,80]. However, there are various factors that must be considered. In order to design a medical instrument, an expertise in CAD modeling is necessary and the labor cost of a designer can be approximately $100–150 per hour [38]. The CAD software license can have an annual cost of approximately $2000 or more and even if free software packages are available, paid software packages are often necessary for complex geometries. Moreover, the design of fine mechanical systems needs a long refinement phase to adapt the CAD design to the 3D-printed results, increasing the labor cost of the designer. A considerable difference in cost is attributed to the type of printer used. FDM is the cheapest technology currently available [99] and the printer cost is approximately $2500 [41,59,57]. However, considering a similar build volume, printers such as multijet (MJ technology), stereolithography (VP technology), or selective laser sintering (PBF technology) have considerably higher costs (Table 3). Other factors that must be taken into consideration are post-processing, sterilization, and energy usage. Among the relevant articles analyzed, only two of them provided a detailed analysis of the costs; in both cases, the FDM technology was used [57,58].

6.4. 3D printing to help and 3D printing to challenge

Looking at the reasons behind the choice of using AM for medical instruments, it is clear that two major application groups can be distinguished: instruments made to help people in developing countries and instruments made to tackle new challenges in terms of design complexity and technical possibilities. Five of the analyzed articles presented ideas to expand the access to medical instrumentation in developing countries. Moreover, there are many non-profit organizations, such as the *ILab/Haiti*, which introduce AM to the locals in order to provide critical medical equipment such as umbilical cord clamps or oxygen splitters in a shorter time with an effective reduction in cost [103]. A similar project is implemented in Tanzania, where the *ReFab Dar* organization is exploring the opportunity of recycling plastic to produce medical supplies such as circumcision kits [104]. The intent of these non-profit organizations is obviously good, but there are still some challenges to be addressed, such as the energy supply required to run the 3D printers and the sterilization of instruments produced [103]. Moreover, there are a number of projects that base the material supply on recycling plastic but the consequences of this choice are not completely clear in terms of durability, mechanical properties, and sterilization. Another important issue that should be taken into

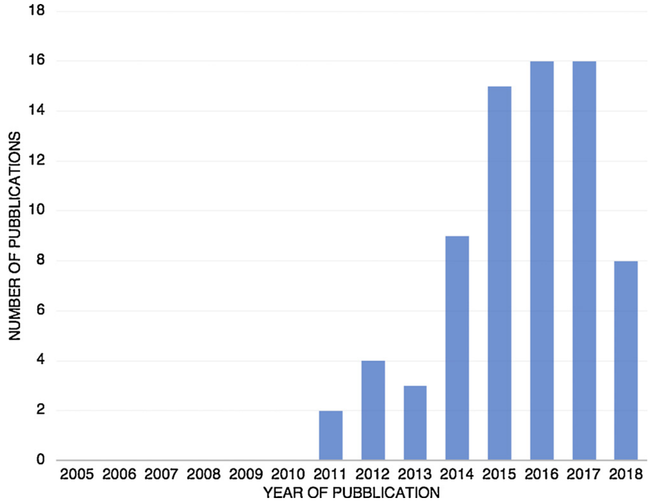

Fig. 10. Temporal distribution of relevant articles found in the literature.

consideration is the possibility of damage to the 3D printers and the need for experts to repair them. Simplifying the 3D printing process is one of the actions for expanding the accessibility and attaining faster and ready-to-use instruments.

A completely opposite trend in AM is to push its boundaries further in the design of highly complex devices capable of performing a new generation of medical procedures. Continuum robots are part of this group [71,67,69,73]. These robots are designed to navigate to inaccessible areas of the human body that are impossible to treat with conventional instrumentation.

6.5. *Temporal distribution and future trends*

AM began to gain importance in the 1980s. Fig. 10 shows how this technology has strongly increased its impact in the field of medical instruments for diagnostics and surgery only in the last eight years. In fact, we did not use any time limitation in our query and no relevant articles dated before 2011 were found. Compared to other medical fields, such as orthoses or surgical planning models, the interest in medical instruments for diagnostics and surgery had grown later [105,106]. This is probably related to the design complexity, advanced functionality, and miniature dimensions of medical instrumentation. The earliest designs for both orthotic and surgical models were only static models based on the images acquired by means of computed tomography scan or MRI without post-processing. On the contrary, it is often not possible to print medical instruments with the exact same design as used with conventional manufacturing to achieve the same functionality. The upward trend can then be considered as the consequence of an increase in knowledge of AM technologies.

In this review, we only considered the seven main categories of AM defined by ASTM. However, new technologies have been invented and tested in the last years. Microscale medical instruments for minimally invasive surgery have been printed by Cohen et al. with the innovative technique of Electrochemical FABrication (EFAB) in which, alternating layers of sacrificial material and structural material, the final device is produced with a layer thickness of 4 µm [107]. Other promising techniques in the micro/nanoscale are Projection Microstereolithography (PµSL) and Direct Ink Writing (DIW) which are widely explained by Mao et al. [108]. PµSL is a 3D printing technology similar to the SLA in which liquid photosensitive materials are polymerized. The high resolution of this technology is given by the combination of a single exposure per layer and the use of micromirror arrays to define the projected mask. DIW is similar to FDM, however, the material is not extruded due to an increase in heat but usually under pressure by exploiting the high viscosity of the material to keep the shape before the post-processing phase. These techniques are mainly used in the bioprinting field, but, given the possibility of printing different types of materials, among which polymers and metals, at a reasonably large volume, possible future applications can be seen in the production of micro-instrumentation, such as instruments for eye surgery, or soft actuators [109].

Improving conventional AM, an interesting direction is followed by Mangat et al. [110]. They use FDM to produce an enhanced material for medical applications by embedding natural fiber into conventional PLA. This idea can find applications not only in bioprinting but also in medical instruments where having tendons directly embedded into the device can lead to a faster assembly as well as more complex geometry in tendon-driven instruments.

Finally, a remarkable new technology is Continuous Liquid Interface Production (CLIP) developed to overcome limitations of SLA [111]. This technology, allows a 3D object to be built continuously without any stop between layers and at a higher speed than in SLA by keeping high resolution [112,113]. The great potential shown by this technology can be foreseen in customization of medical instruments directly before or during surgery due to the high printing speed which allows for on-demand kits in a short time. High-resolution technologies, although still in an initial stage, as well as modified conventional AM have a great impact in the design of medical instruments leading to new designs impossible to produce with conventional manufacturing technologies.

6.6. *Limitations of this study*

This review focuses on the AM of medical instruments for diagnostics and surgery taking into consideration only the seven technologies listed by the ASTM. However, the combination of additive and subtractive manufacturing technologies has not been considered as well as AM technologies such as the EFAB technology able to print medical devices in a microscale [114,107]. Because we only considered articles in which the use of AM is specified, we did not cover papers without a description of the fabrication technology or the material used. A number of AM surgical guides are presented in the literature, mostly in dental interventions and orthopedic surgeries, but they are not included in this review. A comprehensive overview of such devices is provided by Dahake et al. [115] and Popescu et al. [116].

7. Conclusion

This review article provides an overview of the AM of medical instruments used for diagnostics and surgery. We categorized the medical instruments according to the clinical application, novelty, reasons behind the choice of using AM, and the technical characteristics of the AM technologies used. Using AM means having considerable freedom in terms of complexity of the design compared to conventional manufacturing. Several research groups are pushing the boundaries of AM to achieve instruments with advanced functionalities. However, sterilization issues are often ignored. AM is often considered to be an inexpensive and rapid method to produce on-demand medical instruments. The basic material used to print prototypes can be considered inexpensive but the printing technology used is often expensive. On the other hand, the AM technology is opening the door to a personalized treatment that will help people with rare diseases or uncommon anatomy. Moreover, the simple production provides an easier access to healthcare for people who live in developing countries or remote areas. Making use of AM, without disregarding the practical aspects of such a sensitive field, is therefore a great opportunity for designers to develop a new generation of medical instruments with a great impact on society.

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This research is supported by the Netherlands Organization for Scientific Research (NWO), domain Applied and Engineering Sciences (TTW), and which is partly funded by the Ministry of Economic Affairs (project number 12137, Bio-Inspired Maneuverable Dendritic Devices for Minimally Invasive Surgery).

References

[1] C.-Y. Liaw, M. Guvendiren, Current and emerging applications of 3D printing in medicine, Biofabrication 9 (2017) 24102.
[2] D. Hoang, D. Perrault, M. Stevanovic, A. Ghiassi, Surgical applications of three-dimensional printing: a review of the current literature & how to get started, Ann. Transl. Med. 4 (2016).
[3] D.W. Hutmacher, Scaffolds in tissue engineering bone and cartilage, Biomater. Silver Jubil. Compend, Elsevier, 2000, pp. 175–189.
[4] S. Singh, S. Ramakrishna, R. Singh, Material issues in additive manufacturing: a review, J. Manuf. Process. 25 (2017) 185–200.
[5] S. Derakhshanfar, R. Mbeleck, K. Xu, X. Zhang, W. Zhong, M. Xing, 3D bioprinting for biomedical devices and tissue engineering: a review of recent trends and advances, Bioact. Mater. 3 (2018) 144–156.
[6] N. Nagarajan, A. Dupret-Bories, E. Karabulut, P. Zorlutuna, N.E. Vrana, Enabling personalized implant and controllable biosystem development through 3D printing, Biotechnol. Adv. (2018).
[7] J.K. Placone, A.J. Engler, Recent advances in extrusion-based 3D printing for biomedical applications, Adv. Healthc. Mater. 7 (2018) 1701161.
[8] N. Poomathi, S. Singh, C. Prakash, R.V. Patil, P.T. Perumal, V.A. Barathi, K.K. Balasubramanian, S. Ramakrishna, N.U. Maheshwari, Bioprinting in ophthalmology: current advances and future pathways, Rapid Prototyp. J. (2018), https://doi.org/10.1108/RPJ-06-2018-0144.
[9] A. Youssef, S.J. Hollister, P.D. Dalton, Additive manufacturing of polymer melts for implantable medical devices and scaffolds, Biofabrication 9 (2017) 12002.
[10] J. Akmal, M. Salmi, A. Mäkitie, R. Björkstrand, J. Partanen, Implementation of industrial additive manufacturing: intelligent implants and drug delivery systems, J. Funct. Biomater. 9 (2018) 41.
[11] M. Palo, J. Holländer, J. Suominen, J. Yliruusi, N. Sandler, 3D printed drug delivery devices: perspectives and technical challenges, Expert Rev. Med. Devices 14 (2017) 685–696.
[12] W. Lee, D. Kwon, W. Choi, G.Y. Jung, A.K. Au, A. Folch, S. Jeon, 3D-printed microfluidic device for the detection of pathogenic bacteria using size-based separation in helical channel with trapezoid cross-section, Sci. Rep. 5 (2015) 7717, https://doi.org/10.1038/srep07717.
[13] M. Zangheri, L. Cevenini, L. Anfossi, C. Baggiani, P. Simoni, F. Di Nardo, A. Roda, A simple and compact smartphone accessory for quantitative chemiluminescence-based lateral flow immunoassay for salivary cortisol detection, Biosens. Bioelectron. 64 (2015) 63–68, https://doi.org/10.1016/j.bios.2014.08.048.
[14] T. Nozaki, T. Murakami, T. Shimono, K. Ohnishi, R. Oboe, Development of meal assistance device for patients with spinal cord injury, Adv. Motion Control (AMC), 2016 IEEE 14th Int. Work (2016) 388–393.
[15] J. ten Kate, G. Smit, P. Breedveld, 3D-printed upper limb prostheses: a review, Disabil. Rehabil. Assist. Technol. 12 (2017) 300–314.
[16] Y. Jin, J. Plott, R. Chen, J. Wensman, A. Shih, Additive manufacturing of custom orthoses and prostheses–a review, Procedia Cirp 36 (2015) 199–204.
[17] J.S. Cuellar, G. Smit, A. Zadpoor, P. Breedveld, Ten guidelines for the design of non-assembly mechanisms: the case of 3D-printed prosthetic hands, Proc. Inst. Mech. Eng. Part H J. Eng. Med. (2018) 0954411918794734.
[18] M. Salmi, J. Tuomi, K.-S. Paloheimo, M. Paloheimo, R. Björkstrand, A.A. Mäkitie, K. Mesimäki, R. Kontio, Digital design and rapid manufacturing in orbital wall reconstruction, Innov. Dev. Des. Manuf. CRC Press, 2009, pp. 357–360.
[19] J. Poukens, P. Laeven, M. Beerens, G. Nijenhuis, J. Vander Sloten, P. Stoelinga, P. Kessler, A classification of cranial implants based on the degree of difficulty in computer design and manufacture, Int. J. Med. Robot. Comput. Assist. Surg. 4 (2008) 46–50.
[20] N. Xu, F. Wei, X. Liu, L. Jiang, H. Cai, Z. Li, M. Yu, F. Wu, Z. Liu, Reconstruction of the upper cervical spine using a personalized 3D-printed vertebral body in an adolescent with ewing sarcoma, Spine (Phila. Pa. 1976) 41 (2016).
[21] M. Salmi, Possibilities of preoperative medical models made by 3D printing or additive manufacturing, J. Med. Eng. 2016 (2016).
[22] I. Gibson, L.K. Cheung, S.P. Chow, W.L. Cheung, S.L. Beh, M. Savalani, S.H. Lee, The use of rapid prototyping to assist medical applications, Rapid Prototyp. J. 12 (2006) 53–58.
[23] D.B. Jones, R. Sung, C. Weinberg, T. Korelitz, R. Andrews, Three-dimensional modeling may improve surgical education and clinical practice, Surg. Innov. 23 (2016) 189–195.
[24] M. Randazzo, J.M. Pisapia, N. Singh, J.P. Thawani, 3D printing in neurosurgery: a systematic review, Surg. Neurol. Int. 7 (2016) S801.
[25] FDA, Technical Considerations for Additive Manufactured Medical Devices - Guidance for Industry and Food and Drug Administration Staff, (2017).
[26] J.C.F. de Winter, D. Dodou, A surge of p-values between 0.041 and 0.049 in recent decades (but negative results are increasing rapidly too), PeerJ. 3 (2015) e733.
[27] Standard Terminology for Additive Manufacturing Technologies, ASTM International, 2012 A.C.F. on A.M. Technologies, A.C.F. on A.M.T.S.F. 91 on Terminology.
[28] M. George, K.R. Aroom, H.G. Hawes, B.S. Gill, J. Love, 3D printed surgical instruments: the design and fabrication process, World J. Surg. 41 (2017) 314–319, https://doi.org/10.1007/s00268-016-3814-5.
[29] J.Y. Wong, A.C. Pfahnl, 3D printing of surgical instruments for long-duration space missions, Aviat. Sp. Environ. Med. 85 (2014) 758–763, https://doi.org/10.3357/ASEM.3898.2014.
[30] J.Y. Wong, Ultra-portable solar-powered 3D printers for onsite manufacturing of medical resources, Aerosp. Med. Hum. Perform. 86 (2015) 830–834, https://doi.org/10.3357/AMHP.4308.2015.
[31] A.M.S. Ibrahim, R.R. Jose, A.N. Rabie, T.L. Gerstle, B.T. Lee, S.J. Lin, Three-dimensional printing in developing countries, Plast. Reconstr. Surg. - Glob. Open. 3 (2015) e443, https://doi.org/10.1097/GOX.0000000000000298.
[32] S. Kondor, C.G. Grant, P. Liacouras, M.J.R. Schmid, L. Michael Parsons, V.K. Rastogi, L.S. Smith, B. Macy, B. Sabart, C. Macedonia, On demand additive manufacturing of a basic surgical kit, J. Med. Device. 7 (2013) 030916, , https://doi.org/10.1115/1.4024490.
[33] M. George, H. Hawes, K. Aroom, B.S. Gill, J. Love, Inguinal hernia repair using 3D printed surgical instruments in the cadaveric model: a feasibility study, Glob. Surg. 3 (2017) 1–4, https://doi.org/10.15761/GOS.1000156.
[34] D. Paraskevopoulos, Specification analysis, design, and prototyping of a burr hole endoscope stabilization device, Surg. Innov. 23 (2016) 613–619, https://doi.org/10.1177/1553350616660629.
[35] M. del Junco, Z. Okhunov, R. Yoon, R. Khanipour, S. Juncal, G. Abedi, A. Lusch, J. Landam, Development and initial porcine and cadaver experience with three-dimensional printing of endoscopic and laparoscopic equipment, J. Endourol. 29 (2015) 58–62, https://doi.org/10.1016/j.juro.2015.04.029.
[36] I. Yamamoto, R. Ota, R. Zhu, M. Lawn, T. Ishimatsu, T. Nagayasu, K. Takagi, T. Koji, Research on seamless development of surgical instruments based on biological mechanisms using CAD and 3D printer, Biomed. Mater. Eng. 26 (2015) S341–S345, https://doi.org/10.3233/BME-151321.
[37] S. Kondor, C.G. Grant, P. Liacouras, M. Schmid, Personalized surgical instruments, J. Med. Device. 7 (2013), https://doi.org/10.1115/1.4024487.
[38] S.M. Fuller, D.R. Butz, C.B. Vevang, M.V. Makhlouf, Application of 3-dimensional printing in hand surgery for production of a novel bone reduction clamp, J. Hand Surg. Am. 39 (2014) 1840–1845, https://doi.org/10.1016/j.jhsa.2014.06.009.
[39] I. Yamamoto, K. Kishikawa, Y. Kondo, M. Lawn, Development of a Finger Like Multi-Joint Articulated Surgical Retractor for Use in Endoscopic Surgery, 2847 (2018), pp. 1194–1201, https://doi.org/10.21595/jve.2017.19326.
[40] R. Singh, A. Suri, S. Anand, B. Baby, Validation of reverse-engineered and additive-manufactured microsurgical instrument prototype, Surg. Innov. 23 (2016) 606–612, https://doi.org/10.1177/1553350616656282.
[41] T.M. Rankin, N.A. Giovinco, D.J. Cucher, G. Watts, B. Hurwitz, D.G. Armstrong, Three-dimensional printing surgical instruments: are we there yet? J. Surg. Res. 189 (2014) 193–197, https://doi.org/10.1016/j.jss.2014.02.020.
[42] A.A. Kaleev, L.N. Kashapov, N.F. Kashapov, R.N. Kashapov, Application of reverse engineering in the medical industry, IOP Conf. Ser. Mater. Sci. Eng. 240 (2017), https://doi.org/10.1088/1757-899X/240/1/012030.
[43] D.-I. Băilă, I.-G. Ghionea, O.-C. Mocioiu, S. Ćuković, M.-E. Ulmeanu, C.-I. Tarbă, L.-V. Lazăr, Design of handle elevators and ATR spectrum of material manufactured by stereolithography, in: R. Harik, L. Rivest, A. Bernard, B. Eynard, A. Bouras (Eds.), Prod. Lifecycle Manag. Digit. Transform. Ind. Springer International Publishing, Cham, 2016, pp. 309–318.
[44] D.I. Băilă, C.V. Doicin, C.M. Cotruţ, M.E. Ulmeanu, I.G. Ghionea, C.I. Tarbă, Sintering the beaks of the elevator manufactured by direct metal laser sintering (DMLS) process from Co - Cr alloy, Metalurgija 55 (2016) 663–666.
[45] N. Sanchez-Tamayo, J.P. Wachs, Collaborative robots in surgical research: a low-cost adaptation, ACM/IEEE Int. Conf. Human-Robot Interact. (2018) 231–232, https://doi.org/10.1145/3173386.3176978.
[46] C. Aguilera-Astudillo, M. Chavez-Campos, A. Gonzalez-Suarez, J.L. Garcia-Cordero, A low-cost 3-D printed stethoscope connected to a smartphone, Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS (2016) 4365–4368, https://doi.org/10.1109/EMBC.2016.7591694.
[47] S. Rothenberg, S. Abdullah, J. Hirsch, 3D printing prototypes for healthcare professionals: creating a reciprocating syringe, J. Digit. Imaging 30 (2017) 566–571, https://doi.org/10.1007/s10278-017-9953-x.
[48] J.A. Gálvez, A.F. Simpao, Y. Dori, K. Gralewski, N.H. McGill, M.L. Rivera, N. Delso, H. Khan, M.A. Rehman, J.E. Fiadjoe, Not just a pretty face: three-dimensional printed custom airway management devices, 3D Print. Addit. Manuf. 3 (2016) 160–165, https://doi.org/10.1089/3dp.2016.0025.
[49] Y. Way, A.H. Mohamad, Aesyhah, The application of rapid prototyping technology and Quality Functional Deployment (QFD) approach in enhancing the endotracheal tube holder model in medical application, MATEC Web Conf 35 (2015) 2–5, https://doi.org/10.1051/matecconf/20153502005.
[50] R. Kontio, R. Björkstrand, M. Salmi, M. Paloheimo, K.-S. Paloheimo, J. Tuomi, A. Mäkitie, Designing and additive manufacturing a prototype for a novel instrument for mandible fracture reduction, Surg. Curr. Res. (2012), https://doi.org/10.4172/2161-1076.S1-002.
[51] Y. Way, Product development and cost analysis of fabricating the prototype of roller clamp in intravenous (I.V) tubing medical devices using fused deposition modeling (FDM) technology, IOP Conf. Ser. Mater. Sci. Eng. 290 (2018) 12023.
[52] B.M. Walter, A. Hann, R. Frank, A. Meining, A 3D-printed cap with sideoptics for colonoscopy: a randomized ex vivo study, Endoscopy 49 (2017) 808–812, https://

doi.org/10.1055/s-0043-105071.

[53] E.V. Navajas, M. ten Hove, Three-dimensional printing of a transconjunctival vitrectomy trocar-cannula system, Ophthalmologica 237 (2017) 119–122, https://doi.org/10.1159/000457807.

[54] F.R. Cook, E.T. Geier, A.K. Asadi, R.C. Sá, G.K. Prisk, Rapid prototyping of inspired gas delivery system for pulmonary MRI research, 3D Print. Addit. Manuf. 2 (2015) 196–203, https://doi.org/10.1089/3dp.2015.0027.

[55] M. del Junco, R. Yoon, Z. Okhunov, G. Abedi, C. Hwang, B. Dolan, J. Landman, Comparison of flow characteristics of novel three-dimensional printed ureteral stents versus standard ureteral stents in a porcine model, J. Endourol. 29 (2015) 1065–1069, https://doi.org/10.1089/end.2014.0716.

[56] W.J. Ko, G.W. Song, S.P. Hong, C. Il Kwon, K.B. Hahm, J.Y. Cho, Novel 3D-printing technique for caps to enable tailored therapeutic endoscopy, Dig. Endosc. 28 (2016) 131–138, https://doi.org/10.1111/den.12546.

[57] J.M. Walker, D.A. Elliott, C.D. Kubicky, C.R. Thomas, A.M. Naik, Manufacture and evaluation of 3-dimensional printed sizing tools for use during intraoperative breast brachytherapy, Adv. Radiat. Oncol. 1 (2016) 132–135, https://doi.org/10.1016/j.adro.2016.04.001.

[58] M.E. Ulmeanu, C.V. Doicin, D.I. Baila, A.E.W. Rennie, C. Neagu, S. Laha, Comparative evaluation of optimum additive manufacturing technology to fabricate bespoke medical prototypes of composite materials, Mater. Plast. 52 (2015) 416–422.

[59] D.C. Steinemann, P.C. Müller, M. Apitz, F. Nickel, H.G. Kenngott, B.P. Müller-Stich, G.R. Linke, An ad hoc three dimensionally printed tool facilitates intraesophageal suturing in experimental surgery, J. Surg. Res. 223 (2018) 87–93, https://doi.org/10.1016/j.jss.2017.10.026.

[60] F. Jelínek, R. Pessers, P. Breedveld, DragonFlex smart steerable laparoscopic instrument, J. Med. Device 8 (2014) 015001-015001-9, , https://doi.org/10.1115/1.4026153.

[61] F. Jelínek, T. Diepens, S. Dobbenga, G. Van Der Jagt, D. Kreeft, A. Smid, R. Pessers, P. Breedveld, Method for minimising rolling joint play in the steerable laparoscopic instrument prototype DragonFlex, Minim. Invasive Ther. Allied Technol. 24 (2015) 181–188, https://doi.org/10.3109/13645706.2014.968170.

[62] F. Jelínek, P. Breedveld, Design for additive manufacture of fine medical instrumentation—dragonflex case study, J. Mech. Des. 137 (2015) 111416, , https://doi.org/10.1115/1.4030997.

[63] C.A. Seneci, J. Shang, A. Darzi, G.-Z. Yang, Rapid manufacturing with selective laser melting for robotic surgical tools: design and process considerations, 2015 IEEE/RSJ Int. Conf. Intell. Robot. Syst. (2015) 824–830, https://doi.org/10.1109/IROS.2015.7353467.

[64] C.A. Seneci, G. Gras, P. Wisanuvej, J. Shang, G.Z. Yang, 3D printing of improved needle grasping instrument for flexible robotic surgery, IEEE Int. Conf. Intell. Robot. Syst. (2017) 2524–2530, https://doi.org/10.1109/IROS.2017.8206072.

[65] A. Sakes, K. Hovland, G. Smit, J. Geraedts, P. Breedveld, Design of a novel three-dimensional-printed two degrees-of-freedom steerable electrosurgical grasper for minimally invasive surgery, J. Med. Devices, Trans. ASME. 12 (2018), https://doi.org/10.1115/1.4038561 011007-011007-15.

[66] M. Sahlabadi, K. Jezler, P. Hutapea, Novel steerable smart needle with a built-in recovery mechanism for multiple actuations, ASME 2017 Conf. Smart Mater. Adapt. Struct. Intell. Syst. (2017), https://doi.org/10.1115/SMASIS2017-3802 V002T04A012.

[67] K. Oliver-Butler, Z.H. Epps, D.C. Rucker, Concentric agonist-antagonist robots for minimally invasive surgeries, Proc. SPIE 10135, Med. Imaging 2017 Image-Guided Proced. Robot. Interv. Model. 10135 (2017), https://doi.org/10.1117/12.2255549 1013511.

[68] J. Mintenbeck, M. Siegfarth, R. Estaña, H. Wörn, Flexible instrument for minimally invasive robotic surgery using rapid prototyping technology for fabrication, IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM (2014) 1085–1090, https://doi.org/10.1109/AIM.2014.6878225.

[69] Y. Kim, S.S. Cheng, J.P. Desai, Towards the development of a spring-based continuum robot for neurosurgery, Med. Imaging 2015 Image-Guided Proced. Robot. Interv. Model. 9415 (2015), https://doi.org/10.1117/12.2082193 94151Q–9415–6.

[70] D.B. Roppenecker, A. Pfaff, J.A. Coy, T.C. Lueth, Multi arm snake - like robot kinematics, IEEE/RSJ Int. Conf. Intellegent Robot. Syst. (2013) 5040–5045, https://doi.org/10.1109/IROS.2013.6697085.

[71] T.K. Morimoto, A.M. Okamura, Design of 3-D printed concentric tube robots, IEEE Trans. Robot. 32 (2016) 1419–1430, https://doi.org/10.1109/TRO.2016.2602368.

[72] P. Qi, C. Zhang, J. Li, Z. Li, J.S. Dai, K. Althoefer, A compact continuum manipulator system with enhanced steering abilities for robot-assisted surgery, Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics (2016) 49–54, https://doi.org/10.1109/BIOROB.2016.7523597.

[73] E. Amanov, T.-D. Nguyen, J. Burgner-Kahrs, Additive Manufacturing of Patient-Specific Tubular Continuum Manipulators, 9415, (2015), https://doi.org/10.1117/12.2081999 94151P–9415–9.

[74] R. Nowell, B. Shirinzadeh, L. Lai, J. Smith, Y. Zhong, Design of a 3-DOF parallel mechanism for the enhancement of endonasal surgery, IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM (2017) 749–754, https://doi.org/10.1109/AIM.2017.8014107.

[75] A. Schmitz, A.J. Thompson, P. Berthet-Rayne, C.A. Seneci, P. Wisanuvej, G.Z. Yang, Shape sensing of miniature snake-like robots using optical fibers, IEEE Int. Conf. Intell. Robot. Syst. (2017) 947–952, https://doi.org/10.1109/IROS.2017.8202259.

[76] Y.S. Krieger, D.B. Roppenecker, I. Kuru, T.C. Lueth, Multi-Arm snake-like robot, IEEE Int. Conf. Robot. Autom. (2017), pp. 2490–2495.

[77] D.B. Roppenecker, M.F. Traeger, J.D.J. Gumprecht, T.C. Lueth, How to Design and Create a Cardan Shaft for a Single Port Robot by Selective Laser Sintering, (2012), pp. 49–58, https://doi.org/10.1115/IMECE2012-87654.

[78] S. Coemert, M.F. Traeger, E.C. Graf, T.C. Lueth, Suitability evaluation of various manufacturing technologies for the development of surgical snake-like manipulators from metals based on flexure hinges, Procedia Cirp 65 (2017) 1–6, https://doi.org/10.1016/j.procir.2017.03.108.

[79] Q. Boehler, M. Vedrines, S. Abdelaziz, P. Poignet, P. Renaud, Design and evaluation of a novel variable stiffness spherical joint with application to MR-compatible robot design, Proc. - IEEE Int. Conf. Robot. Autom. (2016) 661–667, https://doi.org/10.1109/ICRA.2016.7487192.

[80] K. Entsfellner, I. Kuru, T. Maier, J.D.J. Gumprecht, T.C. Lueth, First 3D printed medical robot for ENT surgery - application specific manufacturing of laser sintered disposable manipulators, IEEE Int. Conf. Intell. Robot. Syst. (2014) 4278–4283, https://doi.org/10.1109/IROS.2014.6943166.

[81] J. Cortes-Rodicio, G. Sanchez-Merino, M.A. Garcia-Fidalgo, I. Tobalina-Larrea, A novel stereotactic frame for real PET-guided biopsies: a preclinical proof-of-concept, Phys. Medica 41 (2017) 124–128, https://doi.org/10.1016/j.ejmp.2017.05.047.

[82] H. Saafi, C. Preault, M.A. Laribi, S. Zeghloul, A novel kinematic of a 4 d.o.fs haptic device based on the delta robot architecture, in: C. Ferraresi, G. Quaglia (Eds.), Adv. Serv. Ind. Robot. Springer International Publishing, Cham, 2018, pp. 699–706.

[83] S.B. Kesner, R.D. Howe, Design principles for rapid prototyping forces sensors using 3D printing, IEEE ASME Trans. Mechatron. 16 (2011) 866–870, https://doi.org/10.1109/TMECH.2011.2160353.

[84] G.A. Fontanelli, L.R. Buonocore, F. Ficuciello, L. Villani, B. Siciliano, A novel force sensing integrated into the trocar for minimally invasive robotic surgery, IEEE Int. Conf. Intell. Robot. Syst. (2017) 131–136, https://doi.org/10.1109/IROS.2017.8202148.

[85] J.I.R. García, J.M.S. Velasco, M.V. Suárez, A.C. Pereira, V. Sosa, J.L.C. Rodríguez, Design engineering in surgery. How to design, test and market surgical devices made with 3 D printing? Cir. Esp. 96 (2018) 198–204, https://doi.org/10.1016/j.ciresp.2017.12.007.

[86] E. Zizer, D. Roppenecker, F. Helmes, S. Hafner, Y. Krieger, T. Luth, A. Meining, A new 3D-printed overtube system for endoscopic submucosal dissection: first results of a randomized study in a porcine model, Endoscopy 48 (2016) 762–765, https://doi.org/10.1055/s-0042-104345.

[87] J. Chen, T. Pickett, A. Langell, A. Trane, B. Charlesworth, K. Loken, S. Lombardo, J.T. Langell, Industry-academic partnerships: an approach to accelerate innovation, J. Surg. Res. 205 (2016) 228–233, https://doi.org/10.1016/j.jss.2016.06.029.

[88] Y.S. Krieger, D.B. Roppenecker, J.U. Stolzenburg, T.C. Lueth, First step towards an automated designed multi-arm snake-like robot for minimally invasive surgery, IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics (2016) 407–412, https://doi.org/10.1109/BIOROB.2016.7523661.

[89] E. Epaminonda, T. Drakos, C. Kalogirou, M. Theodoulou, C. Yiallouras, C. Damianou, MRI guided focused ultrasound robotic system for the treatment of gynaecological tumors, Int. J. Med. Robot. Comput. Assist. Surg. 12 (2016) 46–52, https://doi.org/10.1002/rcs.1653.

[90] G. Menikou, C. Yiallouras, M. Yiannakou, C. Damianou, MRI-guided focused ultrasound robotic system for the treatment of bone cancer, Int. J. Med. Robot. Comput. Assist. Surg. 13 (2017) e1753, https://doi.org/10.1002/rcs.1753.

[91] M. Peikari, T.K. Chen, E.C. Burdette, G. Fichtinger, Section-thickness profiling for brachytherapy ultrasound guidance, Med. Imaging 2011 Vis. Image-Guided Proced. Model. 7964 (2011), https://doi.org/10.1117/12.877993 79640R–79640R–8.

[92] M. Maeda, N. Kanai, S. Kobayashi, T. Hosoi, R. Takagi, T. Ohki, Y. Muragaki, M. Yamato, S. Eguchi, F. Fukai, T. Okano, Endoscopic cell sheet transplantation device developed by using a 3-dimensional printer and its feasibility evaluation in a porcine model, Gastrointest. Endosc. 82 (2015) 147–152, https://doi.org/10.1016/j.gie.2015.01.062.

[93] M.F. Traeger, D.B. Roppenecker, M.R. Leininger, F. Schnoes, T.C. Lueth, Design of a spine-inspired kinematic for the guidance of flexible instruments in minimally invasive surgery, IEEE Int. Conf. Intell. Robot. Syst. (2014) 1322–1327, https://doi.org/10.1109/IROS.2014.6942728.

[94] C. Yiallouras, N. Mylonas, C. Damianou, MRI-compatible positioning device for guiding a focused ultrasound system for transrectal treatment of prostate cancer, Int. J. Comput. Assist. Radiol. Surg. 9 (2014) 745–753, https://doi.org/10.1007/s11548-013-0964-x.

[95] D.B. Roppenecker, A. Meining, G. Horst, H. Ulbrich, T.C. Lueth, Interdisciplinary development of a single-port robot, 2012 IEEE Int. Conf. Robot. Biomimetics, ROBIO 2012 - Conf. Dig. (2012) 612–617, https://doi.org/10.1109/ROBIO.2012.6491034.

[96] A.L. Rugg, L.Y. Nelson, M.-A.I. Timoshchuk, E.J. Seibel, Design and fabrication of a disposable dental handpiece for clinical use of a new laser-based therapy-monitoring system, J. Med. Device. 10 (2015), https://doi.org/10.1115/1.4031800 011005-011005-10.

[97] N. Mylonas, C. Damianou, MR compatible positioning device for guiding a focused ultrasound system for the treatment of brain deseases, Int. J. Med. Robot. Comput. Assist. Surg. 10 (2014) 1–10, https://doi.org/10.1002/rcs.1501.

[98] S. Dikici, B. Aldemir Dikici, H. Eser, E. Gezgin, Ö. Başer, S. Şahin, B. Yılmaz, H. Oflaz, Development of a 2-dof uterine manipulator with LED illumination system as a new transvaginal uterus amputation device for gynecological surgeries, Minim. Invasive Ther. Allied Technol. 27 (2018) 117–185, https://doi.org/10.1080/13645706.2017.1341927.

[99] M.P. Chae, W.M. Rozen, P.G. McMenamin, M.W. Findlay, R.T. Spychal, D.J. Hunter-Smith, Emerging applications of bedside 3D printing in plastic surgery, Front. Surg. 2 (2015) 1–14, https://doi.org/10.3389/fsurg.2015.00025.
[100] W.A. Rutala, D.J. Weber, Guideline for Disinfection and Sterilization in Healthcare Facilities Guideline for Disinfection and Sterilization in Healthcare Facilities 2008 (2008).
[101] H. Shintani, Ethylene oxide gas sterilization of medical devices, Biocontrol Sci. 22 (2017) 1–16.
[102] K.M. Farooqi, F. Mahmood, Innovations in preoperative planning: insights into another dimension using 3D printing for cardiac disease, J. Cardiothorac. Vasc. Anesth. 32 (2018) 1937–1945, https://doi.org/10.1053/j.jvca.2017.11.037.
[103] A.D. Dotz, A pilot of 3D printing of medical devices in Haiti, Technol. Dev. Springer, 2015, pp. 33–44.
[104] ReFab Dar, (n.d.). http://www.refabdar.org/ (accessed July 17, 2018).
[105] D. Freeman, L. Wontorcik, Stereolithography and prosthetic test socket manufacture: a cost/benefit analysis, JPO J. Prosthetics Orthot. 10 (1998) 17–20.
[106] M. McGurk, A.A. Amis, P. Potamianos, N.M. Goodger, Rapid prototyping techniques for anatomical modelling in medicine, Ann. R. Coll. Surg. Engl. 79 (1997) 169.
[107] A. Cohen, R. Chen, U. Frodis, M. Wu, C. Folk, Microscale metal additive manufacturing of multi-component medical devices, Rapid Prototyp. J. 16 (2010) 209–215, https://doi.org/10.1108/13552541011034889.
[108] M. Mao, J. He, X. Li, B. Zhang, Q. Lei, Y. Liu, D. Li, The emerging frontiers and applications of high-resolution 3D printing, Micromachines 8 (2017) 113.
[109] M. Wehner, R.L. Truby, D.J. Fitzgerald, B. Mosadegh, G.M. Whitesides, J.A. Lewis, R.J. Wood, An integrated design and fabrication strategy for entirely soft, autonomous robots, Nature. 536 (2016) 451.
[110] A.S. Mangat, S. Singh, M. Gupta, R. Sharma, Experimental investigations on natural fiber embedded additive manufacturing-based biodegradable structures for biomedical applications, Rapid Prototyp. J. 24 (2018) 1221–1234.
[111] M. Degnan, 3D Printing Techniques and Processes, Cavendish Square Publishing LLC, 2017, https://books.google.nl/books?id=uHlmDwAAQBAJ.
[112] J.R. Tumbleston, D. Shirvanyants, N. Ermoshkin, R. Janusziewicz, A.R. Johnson, D. Kelly, K. Chen, R. Pinschmidt, J.P. Rolland, A. Ermoshkin, Continuous liquid interface production of 3D objects, Science (80-.) (2015) aaa2397.
[113] R.L. Truby, J.A. Lewis, Printing soft matter in three dimensions, Nature 540 (2016) 371.
[114] J. Gafford, Y. Ding, A. Harris, T. McKenna, P. Polygerinos, D. Holland, C. Walsh, A. Moser, Shape deposition manufacturing of a soft, atraumatic, and deployable surgical grasper, J. Mech. Robot. 7 (2015) 021006, , https://doi.org/10.1115/1.4029493.
[115] S.W. Dahake, A.M. Kuthe, M.B. Mawale, A.D. Bagde, Applications of medical rapid prototyping assisted customized surgical guides in complex surgeries, Rapid Prototyp. J. 22 (2016) 934–946.
[116] D. Popescu, D. Laptoiu, Rapid prototyping for patient-specific surgical orthopaedics guides: a systematic literature review, Proc. Inst. Mech. Eng. Part H J. Eng. Med. 230 (2016) 495–515.