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DOI
10.1080/17483107.2016.1253117

Publication date
2017

Document Version
Accepted author manuscript

Published in
Disability and Rehabilitation: Assistive Technology

Citation (APA)
ten Kate, J., Smit, G., & Breedveld, P. (2017). 3D-printed upper limb prostheses: a review. Disability and Rehabilitation: Assistive Technology, 12(3), 300-314. DOI: 10.1080/17483107.2016.1253117

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This is a post-refereeing version of an article whose final and definitive form has been published in the journal 'Disability and Rehabilitation: Assistive Technology', which can be found at: http://dx.doi.org/10.1080/17483107.2016.1253117 (©Informa UK Limited)

3D-Printed upper limb prostheses: A review

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Abstract

GOAL: This paper aims to provide an overview with quantitative information of existing 3D-printed upper limb prostheses. We will identify the benefits and drawbacks of 3D-printed devices to enable improvement of current devices based on the demands of prostheses users.

METHODS: A review was performed using Scopus, Web of Science and websites related to 3D-printing. Quantitative information on the mechanical and kinematic specifications and 3D-printing technology used was extracted from the papers and websites.

RESULTS: The overview (58 devices) provides the general specifications, the mechanical and kinematic specifications of the devices and information regarding the 3D-printing technology used for hands. The overview shows prostheses for all different upper limb amputation levels with different types of control and a maximum material cost of $500.

CONCLUSION: A large range of various prostheses have been 3D-printed, of which the majority are used by children. Evidence with respect to the user acceptance, functionality and durability of the 3D-printed hands is lacking. Contrary to what is often claimed, 3D-printing is not necessarily cheap, e.g., injection moulding can be cheaper. Conversely, 3D-printing provides a promising possibility for individualization, e.g., personalized socket, colour, shape and size, without the need for adjusting the production machine.

Keywords: 3D-printing, hand, prostheses, specifications, upper limb

Introduction

Over the last five years, significant development has occurred in 3D-printing of upper limb prostheses. All over the world people are designing and printing new devices that can easily easy fit a human arm. Scientific papers have been published regarding research in the field of 3D-printed upper limb prostheses [1]-[7]. People are developing prostheses individually, and large communities have been established. Most of the development of 3D-printed prostheses began after the establishment of the global community e-NABLE. This community has grown into a worldwide movement of tinkerers, engineers, 3D-printing enthusiasts, occupational therapists, university professors, designers, parents, families, artists, students, teachers and people who have developed 3D-printed prostheses [8]. It all started with the idea of developing a cheap hand prosthesis [9]. The cost of a commercial body-powered prosthetic hand can range from $4,000 to $10,000 [10], and the cost of an externally powered prosthetic hand can range from $25,000 to $75,000 [10],[11]. The beginning of the development of a 3D-printed hand prosthesis for people who cannot afford an expensive commercial prosthesis resulted in the Robohand, as shown in **Figure 1**.

3D-printing is an additive manufacturing technique. Products are built up layer by layer instead of removing material from a large piece of material, such as in CNC milling. 3D-printing has several advantages compared with other manufacturing techniques [12],[13]:

- It is possible to make products out of one part; therefore, no assembly is required.
- There is large design freedom; therefore, highly complex geometries can be made.
- Designs can easily be personalized and customized; there is no need to change the machine.
- Parts can be produced cheaply and quickly from idea to end product, which gives the advantage of rapid design improvements.

3D-printing also has disadvantages compared to other manufacturing techniques [14],[15]:

- It is hard to predict the mechanical properties. The resulting strength of a part is highly dependent on the fabrication method, and various parameters can be selected depending on the printing orientation.
- The accuracy is highly affected by material shrinkage, different machine parameters and errors induced by the CAD/CAM software as well as post processing.
- The size of an object is limited by the size of the printer. Very large objects cannot be made with current 3D-printing technology.
- 3D-printers can work with a limited amount of materials compared with conventional manufacturing, which can work with nearly any material.

Problem

Although many upper limb prostheses are being 3D-printed all over the world, to the authors' knowledge, there are no specific design guidelines and there is no overview of all of the various devices that have been designed and 3D-printed so far. Some scientific research is ongoing in the field of 3D-printing upper limb prostheses, but currently, most of the 3D-printing of these devices is performed by trial and error.

Goal

Our goal is to provide an overview with quantitative information about existing 3D-printed upper limb prostheses. We will identify the benefits and drawbacks of 3D-printed devices to enable improvements of current devices based on the demands of prostheses users.

Methods

Currently, little information on 3D-printed hand prostheses is available in the peer-reviewed literature. Therefore, information from Internet databases and websites focused on 3D-printing were included. The review consists of two parts: first, the Scopus and Web of Science databases were used; second, an Internet search was performed on three websites:

- www.enablingthefuture.org
- www.3dprint.com
- www.3ders.org

Three websites were used. The first website contains a large database of 3D-printed hand prostheses that have been developed for the worldwide community e-NABLE. The second and third websites provide the most up to date information in the field of 3D-printing. Only unique devices identified through the literature and through website searches were included. Devices based on a similar designs were excluded. Only results in the English language were used in this literature review. The database and Internet searches were carried out using the following keywords: 3D-printing, rapid prototyping, hand, upper limb, prosthetic, prosthetics, and prostheses. Quantitative information on the mechanical and kinematic specifications and 3D-printing technology used were extracted from the papers and websites.

Exclusion and inclusion criteria

Partial finger prostheses and custom prostheses made for handling a specific tool were excluded in the overview. Articles related to the topic that were not found with the search criteria but found from references in other papers were included.

Results

The review resulted in an overview with seven devices found in the scientific literature and 51 devices found on the Internet. The results are presented in three tables. The first table contains general specifications and the mechanical characteristics of the hands. The second table provides information about the kinematics of the hands. The third table provides information from the field of 3D-printing technology that regarding the hands. Each table is divided into two parts. The first part shows the 3D-printed upper limb prostheses found in the scientific literature. The second part of the table shows the devices found from the Internet search. Several specifications or characteristics from the prostheses are unknown and are identified with an "-" symbol in the tables.

Mechanical specifications

Type of prosthesis and type of actuation

The general specifications of the prostheses and mechanical specifications of the fingers are shown in **Table 1**. Some examples of the 3D-printed upper limb prostheses are shown in **Figure 2**. **Table 1** shows the type of prosthesis. These can be specified as three different levels of prostheses:

- Hand (18): The amputation level is a partial hand.
- Forearm (37): The amputation level is below the elbow.
- Upper arm (3): The amputation level is above the elbow.

The various types of actuation for the various types of prostheses are shown in **Figure 3**. All prostheses for people with partial hand loss are body powered. There are four actuation methods for forearm prostheses: two are passive static, one is passive adjustable, 14 are body powered and 20 are externally powered. For externally powered prostheses, 19 are electrically powered and one is powered by pressurized air. All of the upper arm prostheses are externally powered and all are electrically powered.

Type of actuation and type of control

The different types of actuation for the different types of control are shown in **Figure 4**. The two passive static prostheses [37],[50] are a decorative prosthesis, as opposed to the other prostheses, which are more practical and more functional prostheses. One of the prosthesis is passive adjustable [57]. This prosthesis has four rigid fingers and an adjustable thumb that is made by modifying an existing prosthetic hook. The 32 body-powered prostheses can be divided in to prostheses controlled by flexing the thumb (1), flexing the wrist (17), flexing the elbow (4), and through the use of a shoulder harness (4), and for six prostheses, the actuation method was not mentioned. It is unknown how these devices are actuated. Presumably, they can be used with a shoulder harness because they all make use of one output cable that controls all of the fingers. There were 23 prostheses found that are externally powered from, two of which are controlled by electroencephalography (EEG), 20 of which are controlled by electromyography (EMG) and one of which is voice controlled [24].

Weight

The weight of only 11 of the 58 printed upper limb prostheses is specified, as shown in **Table 2**. The lightest device was developed by M. Groenewegen [5] and weighs 71 grams. The heaviest device is the Roboarm developed by Unlimited Tomorrow [54], with a weight of 2000 grams. The remainder of the hands have a weight ranging from 132 grams [21] to 960 grams [6], with most of them (6) ranging from 240 grams [4] to

450 grams [23],[36]. The weight of some of the devices given in the table is not the total weight of the prosthesis:

- Although the Cyborg Beast has the second lowest weight (131.5 grams) compared with the others, this weight is of a prosthesis for a 3 year child. To print this hand for a 16-year-old child, it should be scaled by 140%, which would result in a weight of 184.2 grams [67].
- The Roboarm is a lot heavier than the other prostheses because it is a complete arm. The developers state that it is made from 2 kg of plastic. Therefore, the total weight will be even greater due to the weight of the motors and electronic parts.
- The advanced, low-cost prosthetic arm developed by C. O'Neill weighs 960 grams. This includes a socket, but excludes the haptic feedback sensors [6].
- The weight of the prosthesis developed by K. Andrianesis *et al.* is 350 grams, including a cosmetic glove, but excluding the 180-gram battery [1].

Force distribution

The various types of force distribution between the fingers of each hand are shown in **Figure 5**. The total number of prostheses shown in this figure is 55. The three passive prostheses are excluded. The specifications related to force distribution between the fingers are specified for only a small portion of the hands. For the hands in which the force distribution was not specified, we determined the specifications based on videos and images. The force distribution between the fingers is equal for the majority of hands (28): when the hand is actuated, the force is equally distributed over the fingers. The minority of the prostheses (6) have fingers with force distribution over the fingers, which ensures an adaptive grasp. In these prostheses, the other fingers can still apply a force when some of the fingers are halted by an object. The remainder of the prostheses (21) have fingers with independent force, with one motor per finger. This also enables an adaptive grasp and enables a large variety grasp types.

Type of flexor

The different types of flexors used to close the hand are shown in **Figure 6**. All of the body-powered prostheses found make use of the voluntary closing principal. Voluntary closing devices close when they are actuated and return to their natural open position when the force is released. The majority of devices (45) use cables or non-elastic cords to close the hand. When flexing the wrist or elbow, the cables or cords attached to the end of the fingers ensure that they make a closing grasp. The remainder of the devices make use of a mechanical solution without cables or cords. Nine hands use mechanical linkages controlled by motors, and 1 hand uses compressed air to close the fingers **Error! Reference source not found.**.

Type of extensor

Figure 7 shows the different solutions that are used to open the hand. A large number (36) of prostheses use elasticity to open the hand automatically. This is achieved through the use of elastic cords (21) and elastic bands (4), and a large number of devices use the elasticity of the finger joints (11) to open the hand. The elastic finger joints are called compliant mechanisms. Hands with these compliant mechanisms consist of fingers that are made from one piece where the phalanges are rigid and the joints are flexible. The remainder of the prostheses have cables or cords (11) or mechanical linkages (8), which are, in both, cases attached to motors.

Kinematic specifications

The kinematic specifications of each prosthesis are shown in **Table 3**. The table shows how many joints and degrees of freedom (DOF) a hand has, how many actuators it has, the range of motion of the different joints and the different grasp types a hand can perform. Most of the information in these tables has been estimated based on published images and videos, as it was not mentioned in the publications. For some hands, basic information related to the number of actuators or the DOF was specified. Only Andrianesis [1] and Bahari [2] described their hand in more detail and specified the numbers; the remaining hands lack information related to the kinematic specifications, e.g., DOF´s, ROM and possible grasp type.

Number of joints, DOF and actuators

All of the active hands are underactuated, which means that they have more DOF's than actuators. This is due to the coupling of the phalanges in the fingers. Most of the fingers of the body-powered prostheses consist of 3 phalanges that are connected to each other with cables, cords and so on. The cables from all of the separate fingers are then attached to one linkage, which ensures that the fingers all move at the same time. For externally powered prostheses, the phalanges are connected to each other with cables or mechanical linkages and are directly connected to motors. The motors control the fingers separately.

Range of motion

Each finger of a human hand has four joints. The carpometacarpal (CMC) joint, the metacarpo phalangeal (MCP) joint, the proximal inter-phalangeal (PIP) joint and the distal interphalangeal (DIP) joint [68]. The thumb of a human hand only has three joints. It has no DIP joint, and instead of a PIP joint, it has an interphalangeal (IP) joint, which is described in the table as thumb flexion. The CMC joint of the thumb is also known as the trapeziometacarpal (TMC) joint. This joint is described in the table as thumb circumduction. None of the 3D-printed hands found have a CMC joint. Except for passive hands, all of the hands have an MCP joint and a PIP joint. Only 31 of the 56 active hands have an active DIP joint.

Grasp type

An adaptive grip is the ability of the fingers to conform to the shape of an object held within the hand. In this case, the force is distributed between the fingers, which ensures that some fingers can still apply a force when the others fingers are halted by an object. This can be performed by 24 of the prostheses, of which 18 can do this by controlling the fingers separately by controlling the motors independently. The hand that is actuated with air pressure can perform an adaptive grip by controlling the pressure in the separate fingers with the use of valves. Only five prostheses have a smart mechanism that distributes the force over all of the fingers.

The power grip and precision grip are the two basic grasps a human uses [69]. In addition to these basic grasps, there are four other common types of grasps that are used to perform activities of daily living (ADLs). These four types are the hook grip, spherical grip, tripod grip and lateral grip [70]. All of the active hands (56) can perform a power grip, and the majority (54) can also perform a lateral grip. The precision grip can only be performed by 24 of the hands. Almost one-quarter (14) of the hands can perform all six grasp types, which are, in most cases, electrically powered hands with an adaptive grip.

3D-printing technology used to print the upper limb prostheses

3D-Printing technique

The information related to the 3D-printing technology used to print the prostheses is shown in **Table 4**. The various techniques that are used to print the prostheses are shown in **Figure 8**. Most of the devices (46) are printed using fused deposition modelling (FDM) technology. The remaining prostheses are made using selective laser sintering (SLS) technology (6), selective stereolithography apparatus (SLA) technology (1), and polyjet printing (1), but in the case of four prostheses, the printing technique is unknown. FDM is the only technique that uses a continues filament to print the part. The other techniques make use of a powder or liquid bonded together with the use of a UV laser or UV light.

3D-Printing material

There is a large variety of materials that can be used for 3D-printing. Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the most commonly used materials to print the prostheses. These are the most common materials used for printing with FDM, which is the most commonly used technique to print the devices. The prostheses that are made from flexible materials and FDM 3D-printing make use of NinjaFlex or Filaflex. The chemical name for NinjaFlex is thermoplastic polyurethane [71][71]. Filaflex is a thermoplastic elastomer with a polyurethane base and some additives [72]. Both these materials stay flexible after first being heated and then cooled down. The prostheses made using SLS 3D-printing are made from nylon. SLS 3D-printing most commonly uses standard nylon 11 or nylon 12. The prosthesis made using SLA 3D-printing is made of acrylic plastic, and the prosthesis made using polyjet 3D-printing is made from FullCure 720, which is a photopolymer resin. The Tenim Hand is the only prosthesis that consists of a non-plastic material. This device is made in multiple steps; first, a part from polystyrene is 3D-printed and is then covered with a ceramic layer. The polystyrene is then melted away leaving a cavity in the ceramic that is filled with nylon. This production method is known as the lost wax casting. Therefore, this prosthesis was made using 3D-printing only as a step in the production process.

Production cost

The cost of 20 prostheses are specified and ranges range from \$5 to \$500. The prosthesis that is specified with the lowest cost of \$5 only states the cost of the material that is used for the 3D-printing. The prosthesis that has the greatest specified cost of \$500 states the cost of all of the materials that are needed to manufacture the entire hand (e.g., cables, motors, electronics). There are no prostheses that can be bought off-the-shelf; however, there are some companies working on prostheses that could be sold for \$1,000; for example, You Bionic and Open Bionics are developing a prosthesis that they would like to sell for \$3,000.

Design availability

The designs of 31 of the 58 different printed prostheses are available online. Most of the designs can be found on www.thingiverse.com or www.instructables.com. People can download the CAD-model, print the model and, if necessary, modify the model.

Discussion

A prosthesis should meet the basic user demands to increase the usability of the prosthesis; these demands can be summarized as cosmesis, comfort, control and function [73]. A prosthesis should be beautiful to look at, comfortable to wear, easy to operate and should have a functional use. A limitation of this study was that a great deal of information on the state of the art 3D-printed upper limb prostheses was found on public websites that are not peer-reviewed. However, we believe, in general, the obtained values appear to be in line with values from the literature.

Cosmesis of hand prostheses

After functional factors, the appearance is one of the most important factors in prosthesis rejection [74]. To ensure that a prosthesis has an appealing look, the term anthropomorphic is used in the field of prosthetics. This term refers to the capability of a device to mimic the general aspects of the human hand, such as shape, size, colour, temperature and aesthetic factors [75]. All of the 3D-printed prostheses are designed to resemble the shape of a human hand, except some hands have a thumb that is positioned at 90 degrees or even at 155 degrees with respect to the fingers. The average size of a human hand has a length of 180-198 mm and a width of 75-90 mm [76]. Only the prosthesis developed by Andrianesis specifies the exact dimensions of the prosthesis. The length of this hand is 174 mm and the width is 72 mm. This is slightly smaller than the size of an average human hand. The rest of the hands described in the literature and found on internet do not mention the size. They only mention that the size of the hand can be scaled to match the sound limb. However, this is not possible for hands that are controlled by the wrist. These prostheses are fitted to the residual limb, which results in a bigger hand than the sound hand. The majority of the hands have a brightly coloured appearance. Whereas adults appreciate a more skin-coloured prostheses [77], children may appreciate a coloured appearance [78]. The prostheses developed for adults primarily have a skin colour appearance. Most of the existing conventional prostheses are covered with a cosmetic glove that has a skin coloured look. Currently, two types of cosmetic gloves are available: a polyvinylchloride (PVC) glove and a silicone glove [79][79]. The main function of a cosmetic glove is to cover the mechanism and provide the prosthesis with a natural appearance. In addition to this main function, the glove also protects the mechanism against moisture and dirt. A negative effect of a cosmetic glove is that it results in a greater operational force due to the stiffness of the material. As an extra part for a prosthesis, the glove results in extra costs. None of the 3D-printed hands used a standard glove to cover the mechanism. They are not designed in such a way that a cosmetic glove can cover the mechanism. Only the hand developed by Andrianesis uses a custom fabricated silicone glove. As stated previously, the majority of the hands have a colour that does not look like human skin. These prostheses can also be printed using a filament that has a skin colour to give them a skin-like appearance. The Flexy Hand 2 and the Flexy Hand-Filaflex remix are both made using a skin-coloured filament. Protecting the mechanism from moisture and dirt is one of the advantages of a glove. The disadvantages of a glove are the greater operation force required and the additional cost [79][79]. Printing a prosthesis with skin coloured appearance results no greater operational force needed and no extra cost required to cover the mechanism to give the hand a natural appearance. More than one third of the hands are electrically powered in most cases with a servo motor. This results in a noise that can be an undesired aspect of electrically powered hands. Although all prostheses were designed in the shape of a human hand and the majority of the hands can be scaled to the size of the sound hand, most of them still have a non-anthropomorphic look. The appearance of most of the hands is not similar to the appearance of the sound hand. The majority of the hands look more like a mechanical hand than a cosmetic hand, which might result in a greater prosthesis rejection rate.

Comfort of hand prostheses

A comfortable prosthesis has a good fit and weight that satisfies the user. Almost half of the hands are fitted to the residual limb and tightened using Velcro. The remaining hands can be connected to an existing socket. In the Internet and literature search, the prostheses were found to be easily fitted on the residual limb or connected to an existing socket. No information is published on tests or research that has measured the comfort of these prostheses, and current evidence is mainly anecdotal. The human hand has an average weight of 400±90 grams [80] (distal to the wrist and not including the forearm extrinsic muscles). Excessive weight is one of the most important causes of prostheses rejection [81]. Therefore, it is important to provide the weight specifications of the hand prostheses. For 11 devices, the weight of the hand and part of the arm is specified. For four devices, the weight of only the hand is specified:

- Groenewegen’s hand: 71 gram
- Dextrus EMG: 450 gram
- InMoov 2 hand: 450 gram
- Tact: 350 gram

The Groenewegen’s hand is extremely light. All of the parts for this hand are printed using SLS 3D-printing and are optimized for weight reduction. The other three hands have a comparable weight as the human hand. Comparing the weight of the other seven prostheses shows that six of the prostheses have a similar weight or even a lower weight as similar human arm parts. Only the Cyborg beast has a greater weight than the human body part it replaces. The Cyborg beast is a partial hand prosthesis that replaces the fingers but consists of fingers, a support mechanism and a support to be mounted onto the human hand. The weight of the other partial hand prostheses will probably be greater than the human body part it replaces as well because they are designed in the same way as the Cyborg beast. Although the prostheses that specify a weight have a comparable or slightly lower weight as the human body part it replaces, they are still heavier than some of the commercial available body powered prosthesis [82]. Additionally, it is preferred to have prosthesis that is considerably lighter than 400±90 grams [83]. This preferred weight is highly related to the length of the stump**.** For partial hand prostheses, the weights are greater than the human body part it replaces. To increase the comfort of 3D-printed upper lump prosthesis it is important that specifications related to weight and fitting of future prostheses are provided.

Hand prostheses control

Almost 64% of the hands (37) are developed for people with an amputation level below elbow and 31% of the hands (18) are developed for people with a partial hand amputation level. The remaining hands (3) are developed for people with an amputation level above the elbow. This is remarkable as we compare it to numbers for amputation levels in the USA [84]. The literature shows that approximately 25% have an above elbow amputation level, whereas only three 3D-printed hand prostheses have been developed for this purpose. For partial hand amputation, the literature indicate that these procedures are less than 10%, whereas 31% of the 3D-printed hand prostheses are developed for a partial hand amputation level. The exact numbers for the percentages of passive, body-powered and externally powered prosthesis users are unknown [81]. In general, still a remarkable number of people use a passive cosmetic prosthesis [85], whereas only 2 of the 58 3D-printed hand prostheses are passive prostheses. With respect to the type of actuation for the 3D-printed upper limb prostheses, three of the prostheses are passive, 32 of the prostheses are body-powered and 23 are externally powered. Therefore, the focus of 3D-printed upper limb prostheses is more on body-powered and externally powered than on passive prostheses. Almost 30% of the hands (17) have been developed for people with partial hand loss. These prostheses are body powered and can only be controlled by the wrist. The prostheses developed for all other levels of amputation have a large variety in their type of actuation and type of control.

Hand prostheses function

The total active range of motion of a human finger is 260°, which is the sum of active flexion at the MCP joint (85°), the PIP joint (110°) and the DIP joint (65°) [68]. A little more than one third of the hands (20) have this range of motion as well. The range of motion of the thumb is very important when performing precision grasp. The thumb circumduction ensures this grasp. Less than half of the hands (20) enable active thumb circumduction. More than a third of the hands (24) can perform adaptive grasp. Only five of the hands have a smart mechanism to enable adaptive grasp. The remainder of the hands, which can perform an adaptive grasp, do this by controlling each finger independently with a separate motor. Using a smart mechanism instead of using multiple motors can lead to significant weight reduction [86]. Although the power grip and precision grip are the most important types of grip in daily life, only 24 of the hands can perform these two types of grip. However, almost all of the hands can perform a power grip and a lateral grip. Future hands should focus more on the most important grasp types used in daily live. This can increase the amount of ADLs a person can perform.

The most important aspect of a hand is the ability to perform a secure grip, which is a combination of a grasp type and an applied force. It is only possible to predict the usability of a hand related to tasks if the forces of the hand are specified. Whereas the forces are very important, the forces are only specified from one hand. The Andrianesis' hand can provide fingertip forces of 3.9-11.5 N and has a maximum grip load of 1.5 kg. The fingertip force of a human hand is 30 N [87]. Although the fingertip forces of the Andrianesis' hand are relatively low compared with a human hand, it is still sufficient for most ADLs [68]. There are no specifications provided, such as the actuation force, maximum grip force or maximum load, for the remainder of the hands. Future upper limb prostheses should be tested, and the results should be provided to inform people about the specifications of a hand and to compare the new hand to current hands [82]. Future research should be more focused on providing the specifications of 3D-printed hand prostheses, e.g., the actuation force, maximal grip force, weight, battery life and durability, to allow for better selection between the hands.

3D-printing technology used to print the upper limb prostheses

Every 3D-printing technique has it benefits and drawbacks. These are related to the accuracy of the printing process, possibility of printing different materials and the cost of printing.

3D-Printing technique

The majority of the hands (46) are made using the FDM 3D-printing technique. This technique is the primary technique used worldwide because it uses a relatively cheap printer and is an easy process. A variety of materials can be used, and in most cases, post processing is not required. The downside of FDM is the fact that very small details are difficult to make. FDM has the greatest layer height of all techniques used to print all prostheses, namely approximately 0.15 mm, which results in a rough surface. If overhanging structures need to be made, FDM printing requires support material, which then has to be subsequently removed. SLS is a technique that uses a much more expensive printer but provides a designer with more freedom with respect to shape. A printed part is build up layer by layer by melting powder using a UV laser. The non-melted powder acts as a support material for overhanging structures. The prostheses that are made using SLS printing have a more free form shape compared with the hands that are printed with the use of FDM printing. Smaller details can be printed using SLS compared with FDM because SLS has a lower minimal layer height, namely approximately 100 microns, resulting in a smoother surface compared with FDM. SLS printing does not necessarily require post processing but results in a slightly rough surface. This can be smoothened by polishing or adding a coating. Both SLA and Polyjet printing have the advantage of more design freedom and can print very small details. Both have a very small minimal layer height of approximately 16 microns. The downside of these techniques is that they both need post processing to remove support material, and the material can degrade over time as the photopolymers degrade due to exposure to sunlight [88]. The prostheses made with FDM printing can be printed using a low cost home 3D-printer with a typical cost of approximately $2,000. Prostheses made with SLS, SLA and Polyjet printing are printed using a more expensive industrial printer, especially the SLS and Polyjet printers. SLA printers cost approximately $5,000, whereas the cost of SLS and Polyjet printers can range from $50,000 to $100,000.

Most of the hands do not require small details, which makes FDM printing a suitable technique. Cheap and simple prostheses can be made with the use of this technique. However, due to the limitations of this printing technique, it is difficult to print complex geometries. SLS, SLA and Polyjet printing can be used to print more complex shapes but are more expensive printing process. Moreover, parts made with SLA and Polyjet degrade over time and require post processing to remove the support material [89], so these techniques are not often used in the development of 3D-printed hand prostheses.

3D-Printing material

The majority of the hands are made of ABS and PLA, which are the standard materials used for FDM printing. The materials result in strong parts that barely change with respect to mechanical characteristics over time. Although these rigid parts create a strong hand, the surface of the hand is not compliant. A human hand uses the compliancy of the skin to achieve good grip. The new materials NinjaFlex and Filaflex could be a possible solution to print soft parts as well. A mixture of rigid parts and flexible parts can be used to make a strong prosthesis with a good grip. These flexible materials can be used as printing material for an FDM printer, but some printers have to be adjusted to make sure that the material will not clog the machines [90]. Currently, companies are beginning to develop FDM printers that can extrude multiple materials at the same time [91][92], which could be a big improvement for hands made using FDM technique. A combination of rigid and flexible parts can also be made using Polyjet printing. This duality gives the advantage of printing a combination of different materials in one part. Although only nylon is used to print the devices that are printed with SLS, many materials can be used for printing with SLS even flexible materials. This is also possible for printing with SLA: both rigid and flexible materials can be printed but not at the same time. Most of the hands are made of a rigid material, whereas a combination of rigid and flexible material could improve performance of the hands enabling the addition of a compliant top layer.

Production cost

The prices from only a small number of hands are known. These prices are only the material costs, which are at maximum $500. These costs are hard to compare with the prices from commercially available non 3D-printed upper limb prostheses because these prices consist of more than only the material costs. There are two companies who want to sell their prosthesis as a commercial product. Youbionic [65] is aiming for a price of $1,000 and Open Bionics [40] is aiming for a price of $3,000 for their latest developed Bionic Arm. These hands are both myo-electric hands. Comparing these prices with the commercially available myo-electric hands priced at $25,000 to $75,000, there is a large difference. The developing of cheap hand prostheses can especially be a significant benefit for child prostheses. Children need to change their hand prosthesis quite often due to their growth. By 3D-printing a cheap prosthesis every time, there is no need to purchase an expensive prosthesis regularly. A prosthesis can be scaled to the right size and 3D-printed easily. Although the material costs of 3D-printed hand prostheses can be very low, it is also possible to produce non 3D-printed hand prostheses with a very low material cost. An example of this is the LN-4 Hand [93]. This prosthesis is made by injection moulding six parts with a total production cost of $50. It can be moulded in six minutes. One should be careful in saying that 3D-printed hand prostheses are cheap because the 3D-printer can be expensive by itself. The time and effort of a designer are not included, and 3D-printing is a time consuming production process.

Design availability

More than half of the 3D-printed upper limb prostheses designs are ´open source´ and are available online. Anyone can download a design, criticize and improve the design and post his/her own version of the hand. This can lead to improvements in some hands, as seen in the overview. In the case of some hands, there are already second versions, and there have been some new hands developed based on previous designs. This can lead to fast and cheap improvements in the hands. However, not every 3D-printed prosthesis designer is a prosthetists, and it is very important that the specific needs of the prosthesis user are taken into account.

Prosthesis durability

3D-printing has improved rapidly over the last decade with respect to the design of end-use parts, but when evaluating the 3D-printed upper limb prostheses made currently, they still look like prototype parts. With respect to the durability of the parts, no tests have been carried out to predict the life cycle of the printed parts. No publication mentioned how long a hand could be worn without requiring repair. It was mostly stated that broken parts can easily be replaced by printing new parts [94]. Although most of the hands are printed with the use of FDM printers, it is not always possible to easily print new parts. Firstly, the hands that are not made using FDM printers require parts printed with another technique, which results in more expensive parts or an increased amount of time to obtain the parts. Secondly, the majority of the devices are not printed by the prosthesis user, so the person cannot directly print new parts without contacting a person with a printer. This can result in an unwanted situation where the prostheses cannot be fixed fast enough, which can then result in user not being able to use the prosthesis at all.

Material strength is also an important point to consider. No predictions have been made by the developers of the 3D-printed hands with respect to the strength of the parts of the printed prostheses. This is important because 3D-printing affects the properties of the material. For FDM printing, the material properties of the printed part are not the same as those of the bulk material [95]. For SLS and Polyjet printing, material degradation influences the material properties of the part. Little research has been conducted on current 3D-printed hand prostheses related to material degradation. Some materials degrade over time, especially devices that are made with a photopolymer [88]. Material degradation of the parts will reduce the strength and stiffness of the parts. Further research should be performed on the strength and durability of 3D-printed parts to ensure that future printed hand prostheses require little maintenance and can be worn for a long time.

Benefits and drawbacks of 3D-printing

3D-printing provides promising possibilities to produce complex geometries and custom and personalized designs combined with an ease of manufacturing. However, the mechanical properties, accuracy and the costs have to be taken into account. Plastic parts can be produced cheaper and faster using injection moulding than with 3D-printing, but 3D-printing has the advantage that parts can be easily personalized and customized. 3D-printing has the advantage of being able to produce a custom design without the need to change the production machine. Every prosthesis user has his/her specific needs (e.g., specific tasks a person performs in daily life and the specific fitting to the residual limb). 3D-printing provides the promise of easily producing a personalized socket, printing the prosthesis in the preferred colour, printing a custom shape and size and a design that can be adapted to the needs of the prosthesis user.

Conclusions

This study provides an overview of 58 3D-printed upper limb prostheses that were constructed as part of research, individual projects or worldwide community projects. A large range of different prostheses have been 3D-printed, of which the majority are used by children. Media show children who are happy with their prosthesis, but it remains unclear whether the prosthesis meets the needs of the child. No evidence of short- or long-term use is available. The use could be increased if the 3D-printed upper limb prostheses have greater functionality and a more anthropomorphic appearance. Very little information was found regarding the mechanical specifications of the current hands. Additionally, evidence on the user acceptance, functionality and durability of the 3D-printed hands is lacking. Current evidence is primarily anecdotal. Contrary to media claims, 3D-printed hand prostheses are not always cheap. The material costs are generally cheap, but development, including designing, assembling and fitting the prostheses, has to be taken into account as well. Injection moulding can produce parts much cheaper. Conversely, 3D-printing provides the promising possibility of individualization, e.g., personalized design of the socket, colour, shape and size, without the need to adjust the production machine.

Acknowledgements

We would like to thank Maurice LeBlanc for proofreading and checking the manuscript for grammatical errors.

Declaration of interest

The authors report no declarations of interest.

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Figures

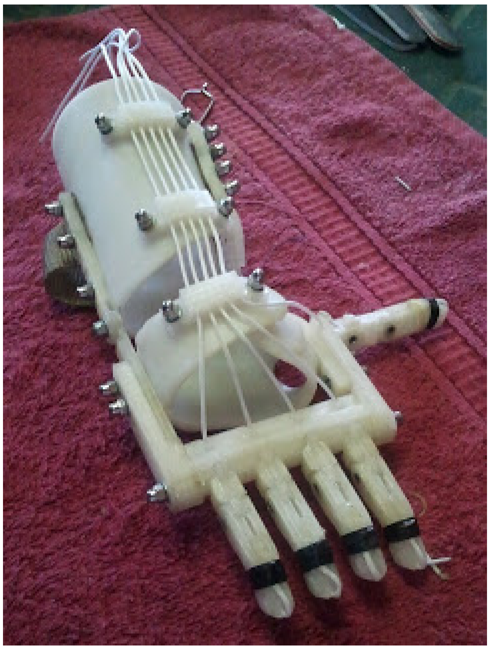
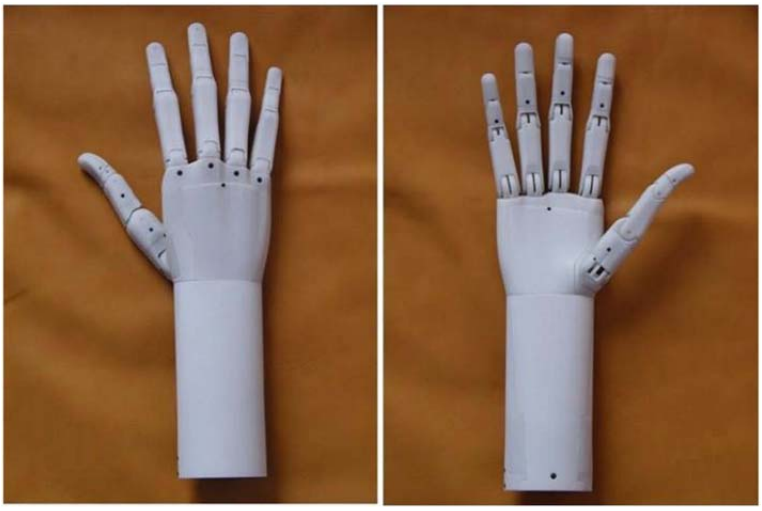


Fig 1. Robohand: The hand that was the inspiration for the development of the global community. Image reproduced with permission from Brod Marsh on behalf of Robohand Australia see http://www.robohand.net/wp-content/uploads/2013/03/2013-03-29-11-10-58-b.jpg, i.e., the copyright holder.



2a

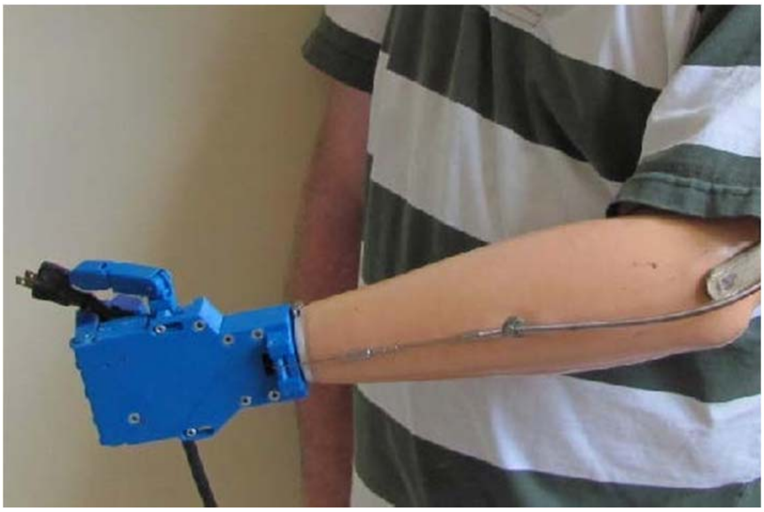


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Fig 2. Examples of 3D-printed upper limb prostheses (a) Andrianesis' Hand: An externally powered forearm prosthesis. Journal of Intelligent & Robotic Systems, Development and Control of a Multifunctional Prosthetic Hand with Shape Memory Alloy Actuators, Volume 78, May 2015, pp 257-289, Konstantinos Andrianesis & Anthony Tzes, with permission of Springer [1]. (b) Gosselin's Hand: A body powered forearm prosthesis. Original source: Mechanical Sciences, Towards the design of a prosthetic underactuated hand vol 1, (2010) pp19-26 Laliberte, et al. No changes made. Reproduced under creative commons attribution 3.0 [3]. (c) Cyborg Beast: A body-powered hand prosthesis. Published with permission of Jorge M. Zuniga [21]. (d) Handiii COYOTE: An externally powered forearm prosthesis. ©exiii, Inc. published with permission [34]. (e) IVIANA 2.0: A passive forearm prosthesis. Published with permission of Evan Kuester [37]. (f) Scand: A passive adjustable forearm prosthesis. Original source http://www.instructables.com/id/3D-Printing-Prosthetic-Hand-Make-it-Real-Challen/ Scott Allen. No changes made. Reproduced under creative commons attribution 3.0 [57].

a) Andrianesis' Hand
b) Gosselin's Hand
c) Cyborg Beast
d) Handiii COYOTE
e) IVIANA 2.0
f) Scand

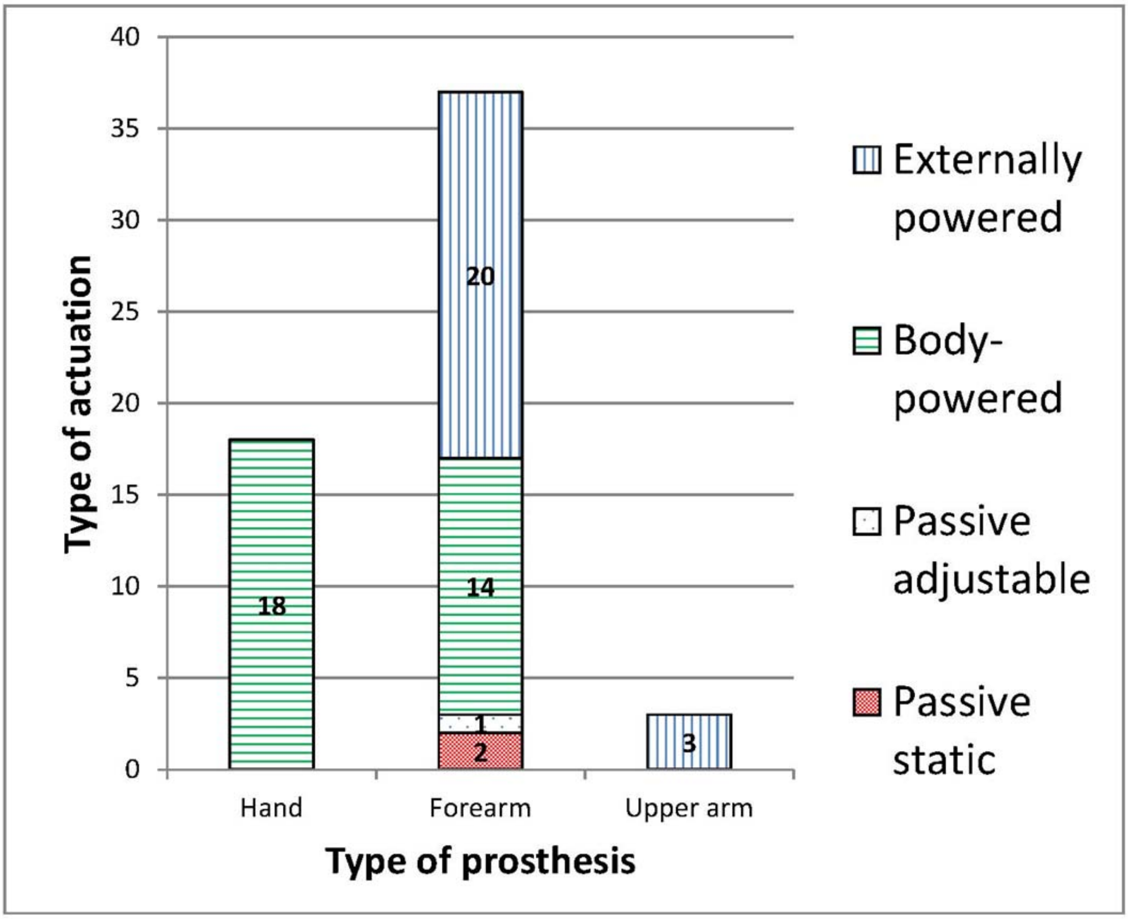

Fig 3. Almost two-thirds of the devices are forearm prostheses from which slightly more than half of the devices are externally powered.

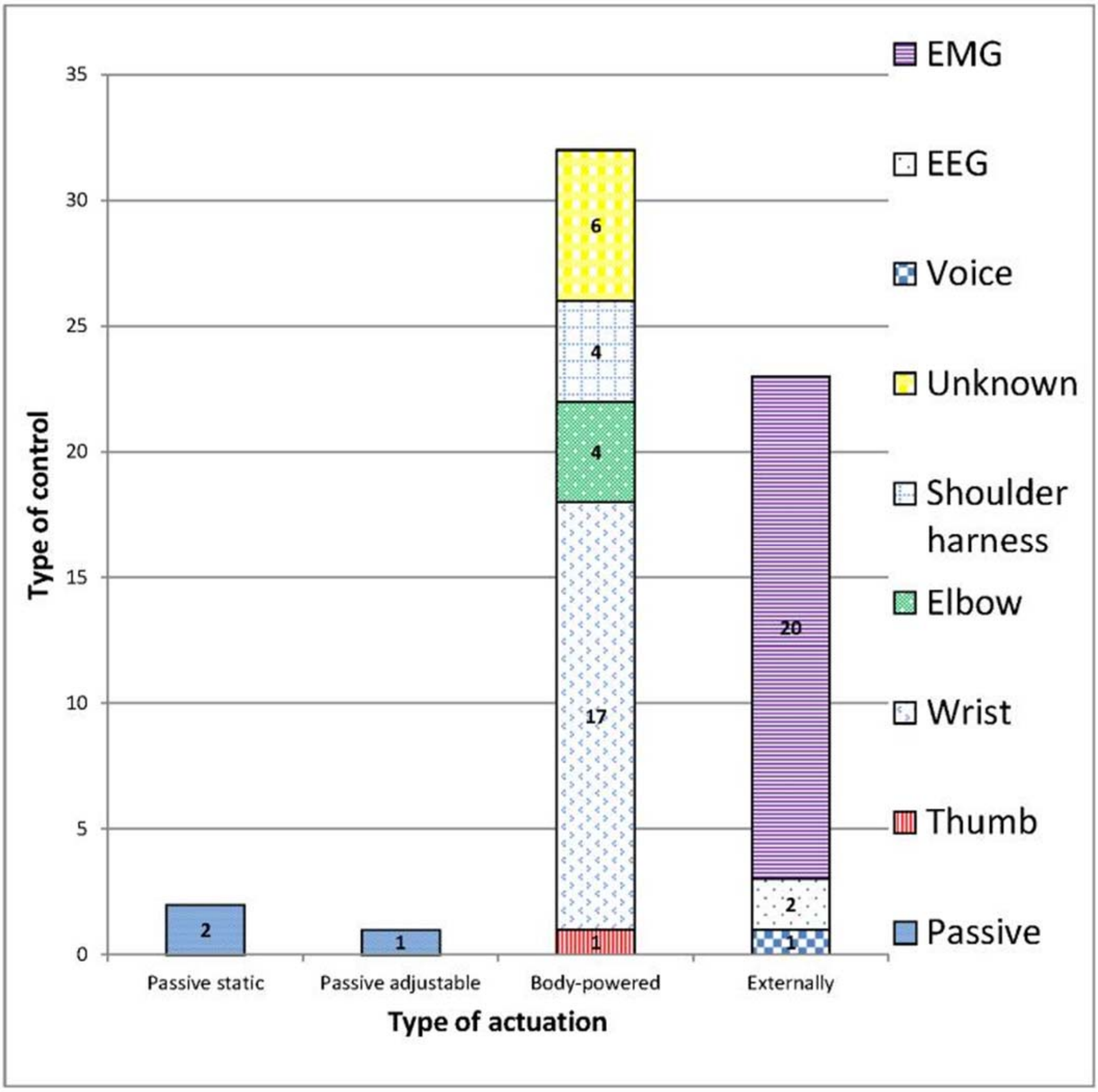

Fig 4. Slightly more than half of all of the prostheses are body powered from which slightly more than half of the devices are controlled by the wrist.

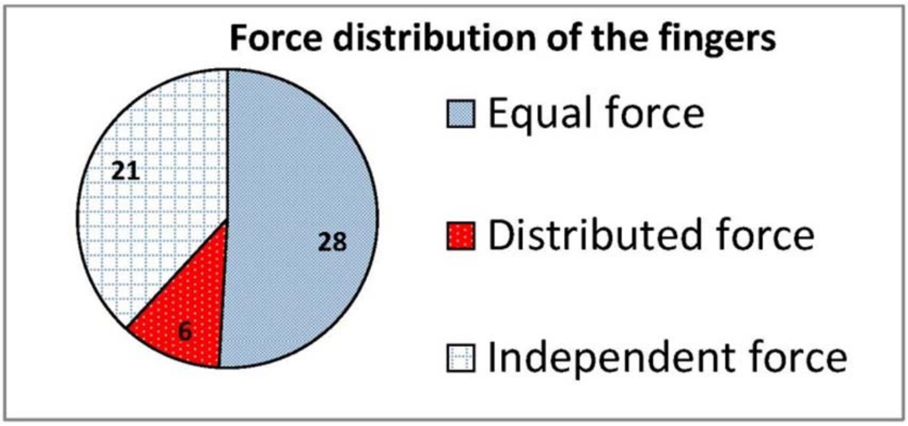

Fig 5. More than half of the actuated hands have an equal force between the fingers. Slightly more than a third of the hands have fingers with independent force due to a separate motor for each finger. Only a small number of the hands have a mechanical linkage system to distribute the force along the fingers

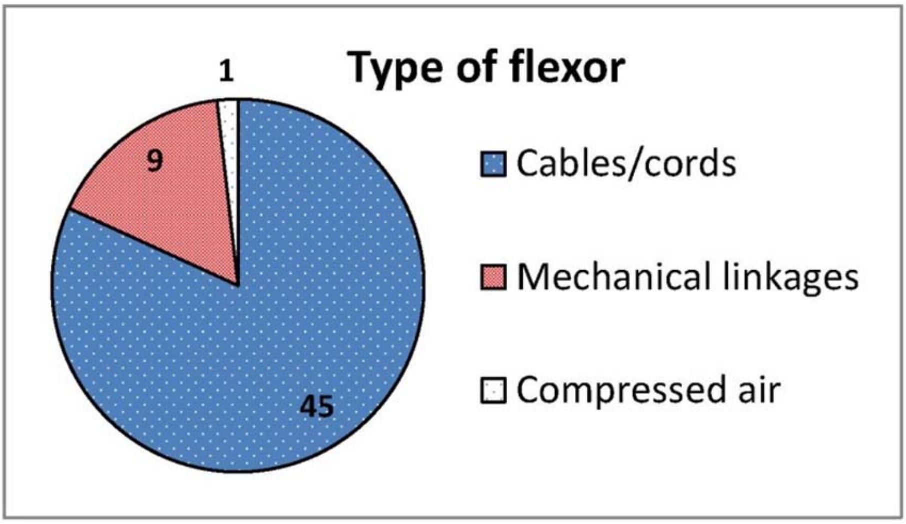

Fig 6. The type of flexor used to close the prosthesis. The majority of the hands use cables or cords to close the hand. The remainder of the hands use mechanical linkages and one uses compressed air.

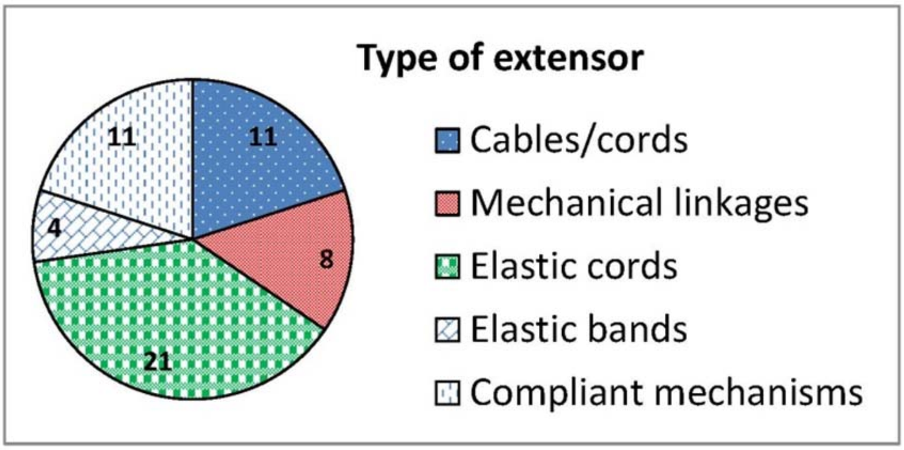

Fig 7. The type of extensor used to open the prosthesis. Almost two thirds of the hands use elasticity in the form of elastic cords or bands or compliant mechanisms to open the hand automatically.

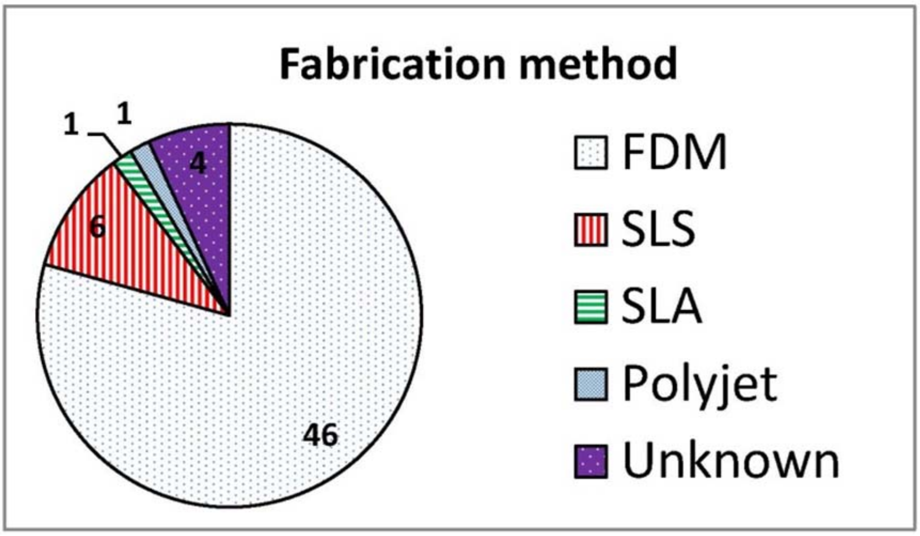

Fig 8. The various fabrication methods used to print the prostheses. The majority of the devices are made using FDM technology

Table 1: General specifications and mechanical specifications of the 3D-printed hand prostheses.

	Type of Prosthesis	Type of Actuation	Type of Control	Weight (g)	Force distribution	Flexor	Extensor
Prostheses found in the scientific literature							
Andrianesis' Hand [1] **Fig. 2a**	Forearm	EP	EMG	350	Independent	Cables/cords	ML
Bahari's Hand [2]	Forearm	EP	EMG	-	Independent	ML	Cables/cords
Gosselin's Hand [3] **Fig. 2b**	Forearm	BP	SH	-	Distributed	Cables/cords	Cables/cords
Gretsch' Hand [4]	Forearm	EP	EMG	240	Independent	Cables/cords	Elastic cords
Groenewegen's Hand [5]	Forearm	BP	-	71	Distributed	ML	CM
O'Neill's Hand [6]	Forearm	EX	EMG	960	Independent	Cables/cords	Cables/cords
Simone's Hand [7]	Forearm	EP	EMG	-	Independent	Cables/cords	Cables/cords
Prostheses found by performing an internet search							
3D-printed prosthesis Ecuador [16]	Forearm	EP	EMG	-	Independent	Cables/cords	Cables/cords
Adjustable Thumb [17]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Biohand [18]	Forearm	EP	EMG	-	Independent	ML	ML
Bionico hand [19]	Forearm	EP	EMG	-	Independent	Cables/cords	Cables/cords
Cyborg Arm [20]	Forearm	BP	Elbow	-	Equal	Cables/cords	Elastic cords
Cyborg Beast [21] **Fig. 2c**	Hand	BP	Wrist	1.315	Equal	Cables/cords	Elastic cords
Cyborg Beast with I.W.M. [22]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Dextrus EMG [23]	Forearm	EP	EMG	450	Independent	Cables/cords	Cables/cords
DIY Prosthetic Hand & Forearm [24]	Forearm	EP	Voice	-	Independent	Cables/cords	Cables/cords
Falcon Hand V1 [25]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic bands
Falcon Hand V2 [26]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic bands
Flexy Arm [27]	Forearm	BP	Elbow	-	Equal	Cables/cords	CM
Flexy Hand [28]	Forearm	BP	-	-	Equal	Cables/cords	CM
Flexy Hand 2 [29]	Hand	BP	Wrist	-	Equal	Cables/cords	CM
Flexy Hand - Filaflex remix [30]	Forearm	BP	-	-	Equal	Cables/cords	CM
GalileoHand [31]	Forearm	BP	SH	-	Equal	Cables/cords	Elastic cords
HACKberry [32]	Forearm	EP	EMG	-	Independent	ML	ML
Handiii [33]	Forearm	EP	EMG	-	Independent	ML	ML
Handiii COYOTE [34] **Fig. 2d**	Forearm	EP	EMG	750	Independent	ML	ML
Hollies Hand [35]	Hand	BP	Wrist	-	Equal	Cables/cords	CM
InMoov 2 hand [36]	Forearm	EP	EMG	450	Independent	ML	ML
IVIANA 2.0 [37] **Fig. 2e**	Forearm	PS	N/A	-	N/A	N/A	N/A
JD-1 [38]	Forearm	BP	-	-	Distributed	Cables/cords	CM
K-1 [39]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Latest Bionic arm [40]	Forearm	EP	EMG	250	Independent	Cables/cords	CM
Limbitless Arm [41]	Upper arm	EP	EMG	-	Equal	Cables/cords	CM
Manu Print (Re Hand) [42]	Forearm	BP	-	-	Distributed	Cables/cords	Elastic cords
Mind Controlled Robotic Hand [43]	Upper arm	EP	EEG	-	Independent	Cables/cords	Cables/cords
Muscle Robot Hand [44]	Forearm	EP	EMG	-	Independent	Compressed air	CM
Not Impossible [45]	Forearm	BP	Elbow	-	Equal	Cables/cords	Elastic cords
Nu Hand [46]	Forearm	EP	EMG	-	Independent	Cables/cords	Elastic cords
Odysseus Hand [47]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
One-hinged Cyborg Beast [48]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Prosthetic/Robotic Hand [49]	Forearm	BP	-	-	Equal	Cables/cords	Elastic bands
Prótesis Cosmética [50]	Forearm	PS	N/A	-	N/A	N/A	N/A
Raptor Hand [51]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Raptor Reloaded [52]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
RIT Arm [53]	Forearm	BP	Elbow	-	Equal	Cables/cords	Elastic cords
Roboarm [54]	Upper arm	EP	EEG	2000	Independent	Cables/cords	Cables/cords
Robohand [55]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Robot Hand [56]	Forearm	EP	EMG	-	Equal	Cables/cords	CM
Scand [57] **Fig. 2f**	Forearm	PA	N/A	-	N/A	N/A	N/A
Snap-Together Robohand [58]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Tact [59]	Forearm	EP	EMG	350	Independent	Cables/cords	Elastic bands
Talon Flextensor 1.0 [60]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Talon Hand 2.0 [61]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords
Tenim Hand [62]	Forearm	BP	SH	-	Distributed	Cables/cords	Cables/cords
The Lucky Paw Prosthetic Hand [63]	Hand	BP	Finger	-	Equal	Cables/cords	Elastic cords
Victory Hand [64]	Forearm	BP	SH	-	Distributed	ML	ML
Youbionic [65]	Forearm	EP	EMG	-	Independent	ML	ML
Zero Point Frontiers [66]	Hand	BP	Wrist	-	Equal	Cables/cords	Elastic cords

BP = body-powered, EP = externally powered, PS = passive static, PA = passive adjustable, SH = shoulder harness

ML = mechanical linkages, CM = compliant mechanisms

Table 2:
Weight of the 3D-printed hand prostheses. Only 11 of the 58 3D-printed upper limb prostheses specified their weights.

	Weight (g)
Andrianesis' hand [1]	350
Gretsch' Hand [4]	240*
Groenewegen's Hand [5]	71†
O'Neill's Hand [6]	960
Cyborg Beast [21]	131.5
Dextrus EMG [23]	450
Handiii COYOTE [34]	750
InMoov 2 Hand [36]	450†
Latest Bionic arm [40]	250
Roboarm [54]	2000
Tact [59]	350†

***Estimated weight by the developers**

† Excluding connector or socket to fit a human arm

Table 3:
Kinematic specifications of the 3D-printed hand prostheses

				Range of motion					Grasp Type	
	Joints	DOF	Actuators	MCP Joints (°)	PIP Joints (°)	DIP Joints (°)	Thumb Flexion (°)	Thumb Circum-duction (°)	Adaptive Grip	Achievable Grasps
Prostheses found in scientific literature										
Andrianesis' Hand [1] **Fig. 2a**	15	15	9	0-105	0-90	0-25	0-90	0-50	Yes, Me.	Power, precision, lateral + H,T,S
Bahari's Hand [2]	14	14	5	0-80	0-100	0-65	0-80	N/A	Yes, El.	Power, hook, spherical
Gosselin's Hand [3] **Fig. 2b**	15	15	1 (BP)	0-90	0-90	0-90	0-90	0-25	Yes, Me.	Power, precision, lateral
Groenewegen's Hand [4]	15	15	1 (BP)	0-90	0-45	0-45	0-90	N/A	Yes, Me.	Power, lateral
Gretsch' Hand [5]	10	10	5	0-100	0-90	N/A	0-90	N/A	Yes, El.	Power, hook, lateral
O'Neill's Hand [6]	15	15	5	0-90	0-90	0-90	0-45	0-90	Yes, El.	Power, precision, lateral
Simone's Hand [7]	15	15	5	0-110	0-90	0-90	0-45	N/A	Yes, El.	Power, precision
Prostheses found with the internet search										
3D-printed prosthesis Ecuador [16]	15	15	5	0-90	0-90	0-90	0-90	0-90	Yes, El.	Power, precision, lateral + H,T,S
Adjustable Thumb [17]	11	11	1 (BP)	0-45	0-60	N/A	0-60	N/A	No	Power, precision, lateral
Biohand [18]	10	10	5	0-90	0-90	N/A	N/A	0-45	Yes, El.	Power, precision, lateral
Bionico hand [19]	16	16	5	0-75	0-90	0-80	0-90	0-45	Yes, El.	Power, precision, lateral + H,T,S
Cyborg Arm [20]	10	10	1 (BP)	0-45	0-60	N/A	0-60	N/A	No	Power, lateral
Cyborg Beast [21] **Fig. 2c**	10	10	1 (BP)	0-45	0-60	N/A	0-60	N/A	No	Power, lateral
Cyborg Beast with I.W.M. [22]	10	10	1 (BP)	0-45	0-60	N/A	0-60	N/A	No	Power, lateral
Dextrus EMG [23]	15	15	5	0-90	0-90	0-90	0-90	0-90	Yes, El.	Power, precision, lateral + H,T,S
DIY Prosthetic Hand & Forearm [24]	16	16	5	0-75	0-90	0-80	0-90	0-45	Yes, El.	Power, precision, lateral + H,T,S
Falcon Hand V1 [25]	13	13	1 (BP)	0-90	0-90	0-45	0-90	N/A	No	Power, lateral
Falcon Hand V2 [26]	11	11	1 (BP)	0-90	0-90	N/A	0-90	0-90	No	Power, Precision, lateral
Flexy Arm [27]	14	14	1 (BP)	0-45	0-80	0-45	0-30	N/A	No	Power, lateral
Flexy Hand [28]	14	14	1 (BP)	0-45	0-80	0-45	0-30	N/A	No	Power, precision, hook, lateral
Flexy Hand 2 [29]	14	14	1 (BP)	0-45	0-80	0-45	0-30	N/A	No	Power, lateral
Flexy Hand - Filaflex remix [30]	15	14	1 (BP)	0-90	0-90	0-45	0-30	N/A	No	Power, lateral
GalileoHand [31]	11	11	1 (BP)	0-90	0-90	N/A	0-90	0-90	No	Power, Precision, lateral
HACKberry [32]	10	10	6	0-90	0-90	N/A	N/A	0-90	Yes, El.	Power, Precision, lateral
Handiii [33]	15	15	6	0-90	0-90	0-90	0-90	0-90	Yes, El.	Power, precision, lateral + H,T,S
Handiii COYOTE [34] **Fig. 2d**	15	15	6	0-90	0-90	0-90	0-90	0-90	Yes, El.	Power, precision, lateral + H,T,S
Hollies Hand [35]	10	10	1 (BP)	0-45	0-20	N/A	0-20	N/A	No	Power, lateral
InMoov 2 hand [36]	15	15	4	0-90	0-90	0-90	0-90	0-45	Yes, El.	Power, precision, lateral
IVIANA 2.0 [37] **Fig. 2e**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
JD-1 [38]	14	14	1 (BP)	0-45	0-45	0-45	0-45	N/A	No	Power, lateral
K-1 [39]	14	14	1 (BP)	0-90	0-90	0-45	0-90	N/A	No	Power, lateral
Latest Bionic arm [40]	15	15	5	0-90	0-45	0-20	0-90	0-60	Yes, El.	Power, precision, lateral + H,T,S
Prostheses found with the internet search										
Limbitless Arm [41]	14	14	1 (BP)	0-45	0-80	0-45	0-30	N/A	No	Power, precision, hook, lateral
Manu Print (Re Hand) [42]	14	14	1 (BP)	0-90	0-90	0-45	0-45	N/A	Yes, Me.	Power, lateral
Mind Controlled Robotic Hand [43]	16	16	5	0-75	0-90	0-80	0-90	0-45	Yes, El.	Power, precision, lateral + H,T,S
Muscle Robot Hand [44]	5	>5	1(Air)	0-90	0-90	0-90	0-90	N/A	Yes, Pneumatic	Power, lateral
Not Impossible [45]	10	10	1 (BP)	0-90	0-90	N/A	0-60	N/A	No	Power, lateral
Nu Hand [46]	19	19	1 (BP)	0-90	0-90	0-90	0-90	0-30	No	Power, precision, lateral + H,T,S
Odysseus Hand [47]	6	6	1 (BP)	0-90	0-45	N/A	0-45	N/A	No	Power, lateral
One-hinged Cyborg Beast [48]	8	8	1 (BP)	0-45	0-60	N/A	No Thumb	No Thumb	No	Power
Prosthetic/Robotic Hand [49]	15	15	1 (BP)	0-90	0-90	0-90	0-90	N/A	No	Power, lateral
Prótesis Cosmética [50]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Raptor Hand [51]	10	10	1 (BP)	0-80	0-90	N/A	0-70	N/A	No	Power, lateral
Raptor Reloaded [52]	10	10	1 (BP)	0-80	0-90	N/A	0-90	N/A	No	Power, lateral
RIT Arm [53]	14	14	1 (BP)	0-90	0-45	N/A	0-30	N/A	No	Power, lateral

Roboarm [54]	14	14	5	0-90	0-90	0-90	0-90	N/A	Yes, El.	Power, precision, lateral + H,T,S
Robohand [55]	10	10	1 (BP)	0-90	0-90	N/A	0-90	N/A	No	Power, lateral
Robot Hand [56]	15	15	1 (BP)	0-90	0-90	0-90	0-90	N/A	No	Power, spherical
Scand [57] **Fig. 2f**	1	1	1(BP)	N/A	N/A	N/A	0-90	N/A	No	Power, lateral
Snap-Together Robohand [58]	10	10	1 (BP)	0-90	0-90	N/A	0-90	N/A	No	Power, lateral
Tact [59]	11	11	6	0-90	0-90	N/A	0-90	0-90	Yes, El.	Power, precision, lateral + H,T,S
Talon Flextensor 1.0 [60]	10	10	1 (BP)	0-100	0-45	N/A	0-90	N/A	No	Power, lateral
Talon Hand 2.0 [61]	10	10	1 (BP)	0-90	0-90	N/A	0-90	N/A	No	Power, lateral
Tenim Hand [62]	15	15	1(BP)	0-90	0-90	0-90	0-90	0-90	Yes, Me.	Power, precision, lateral + H,T,S
The Luck Paw Prosthetic Hand [63]	12	12	1 (BP)	0-90	0-90	0-90	No Thumb	No Thumb	No	Power
Victory Hand [64]	14	14	1 (BP)	0-90	0-45	0-45	0-45	0-90	No	Power, Precision, lateral
Youbionic [65]	11	11	5	0-90	0-90	N/A	0-45	0-45	Yes, El.	Power, precision, lateral + H,T,S
Zero Point Frontiers [66]	6	6	1 (BP)	0-90	0-45	N/A	No Thumb	No Thumb	No	Power

BP = body powered, Me. = mechanical, El. = electrical, H,T,S = hook, tripod, spherical

Table 4:
Print specifications of the 3D-printed hand prostheses. The first part of the table shows the 3D-printed upper limb prostheses found in scientific literature and the second part of the table shows the devices found with the internet search.

	Fabrication method	Material	Material cost ($)	Design availability
Prostheses found in scientific literature				
Andrianesis’ Hand [1] **Fig. 2a**	SLS	Duraform HST	-	No
Bahari’s Hand [2]	SLA	Acrylic plastic	-	No
Gosselin’s Hand [3] **Fig. 2b**	FDM	ABS	-	No
Gretsch’ Hand [4]	FDM	ABS	300	No
Groenewegen’s Hand [5]	SLS	Nylon	-	No
O’Neill’s Hand [6]	FDM	ABS	500	No
Simone’s Hand [7]	Polyjet	Full Cure 720	-	No
Prostheses found with the internet search				
3D-printed prosthesis Ecuador [16]	FDM	-	270	No
Adjustable Thumb [17]	FDM	ABS	-	No
Biohand [18]	FDM	-	±300	No
Bionico hand [19]	FDM	ABS	250	Yes
Cyborg Arm [20]	FDM	ABS	-	No
Cyborg Beast [21] **Fig. 2c**	FDM	ABS	50	Yes
Cyborg Beast with I.W.M. [22]	FDM	ABS	-	No
Dextrus EMG [23]	FDM	PLA or ABS	±1000	Yes
DIY Prosthetic Hand & Forearm [24]	FDM	-	-	Yes
Falcon Hand V1 [25]	FDM	ABS	-	Yes
Falcon Hand V2 [26]	FDM	ABS	-	Yes
Flexy Arm [27]	FDM	FLA & Filaflex	-	Yes
Flexy Hand [28]	FDM	FLA & Filaflex	-	Yes
Flexy Hand 2 [29]	FDM	FLA & Filaflex	-	Yes
Flexy Hand - Filaflex remix [30]	FDM	Filaflex	-	Yes
GalileoHand [31]	FDM	PLA or ABS	-	Yes
HACKberry [32]	FDM	-	200	Yes
Handiii [33]	Unknown	-	300	No
Handiii COYOTE [34] **Fig. 2d**	Unknown	-	300	No
Hollies Hand [35]	SLS	Nylon	-	Yes
InMoov 2 hand [36]	FDM	-	-	Yes
IVIANA 2.0 [37] **Fig. 2e**	Unknown	-	-	No
JD-1 [38]	FDM	Nylon	-	No
K-1 [39]	FDM	-	-	No
Latest Bionic arm [40]	FDM	-	±3000	No
Limbitless Arm [41]	FDM	ABS & Ninjaflex	350	Yes
Manu Print (Re Hand) [42]	FDM	-	20	No
Mind Controlled Robotic Hand [43]	FDM	ABS	500	Yes
Muscle Robot Hand [44]	FDM	PLA & Silicone	-	Yes
Not Impossible [45]	FDM	-	100	No
Nu Hand [46]	FDM	-	-	No
Odysseus Hand [47]	FDM	ABS	-	Yes
One-hinged Cyborg Beast [48]	FDM	ABS	-	Yes
Prosthetic/Robotic Hand [49]	FDM	PLA	1	Yes
Prótesis Cosmética [50]	Unknown	-	-	No
Raptor Hand [51]	FDM	PLA	-	Yes
Raptor Reloaded [52]	FDM	PLA	-	Yes
RIT Arm [53]	FDM	-	-	Yes
Roboarm [54]	FDM	PLA	350	Yes
Robohand [55]	FDM	ABS	500	Yes
Robot Hand [56]	FDM	ABS & flexible plastic	-	Yes
Scand [57] **Fig. 2f**	SLS	DM_9795 & DM_9770	-	No
Snap-Together Robohand [58]	FDM	PLA	-	Yes
Tact [59]	FDM	-	250	Yes
Talon Flextensor 1.0 [60]	FDM	ABS	-	Yes
Talon Hand 2.0 [61]	FDM	ABS	-	Yes
Tenim Hand [62]	SLS	Nylon with ceramic layer	-	No
The Lucky Paw Prosthetic Hand [63]	FDM	-	-	Yes
Victory Hand [64]	FDM	-	100	No
Youbionic [65]	SLS	Nylon	±1000	No
Zero Point Frontiers [66]	FDM	PLA	5	No