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REVIEW

3D printed upper limb prosthetics

Ivan Vujaklija and Dario Farina

Department of Bioengineering, Imperial College London, London, UK

ABSTRACT

Introduction: In the last 15 years, the market for prosthetic arms and hands has shifted toward systems with greater degrees of actuation. There has also been a progressive use of emerging technologies to overcome hardware design challenges. Moreover, the proliferation of rapid prototyping has resulted in applications in the prosthetic market. Even though there are concerns on robustness and wide-user acceptance, the affordable and customizable solution offered by rapid prototyping, combined with the possibility for easy maintenance and repair, is very attractive for prosthesis design.

Areas covered: Functional layouts for multi-articulated, dexterous 3D printed hands and sockets are freely available, with many patients using them at home. We provide an overview of the current solutions, compare their features, and discuss their potential impact on the field of prosthetics.

Expert commentary: The high level of low-cost customization is an appealing concept, but this comes with challenges not yet systematically addressed; such challenges include durability, sufficient grip strength, reproducibility, and general appeal to the wide range of users. The introduction of new printable materials could assist in overcoming some of these issues, but present an added risk of compromising the low cost and wide availability.

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1. Introduction

The first recorded artificial upper limb dates back to 200 BC when a Roman general who lost his hand during a war was fitted with a fully iron casted prosthetic [1]. This bulky prosthetic design has since been steadily improved, with major design changes coinciding with grand engineering discoveries. However, it was only in 1912, when Bowden cables had already become an industry standard, that the first functional upper limb prosthetic was patented as a split hook [2] that is still widely present on the market [3]. Shortly after the introduction of the hook, following the improvement of the electrical motors, the first electrically powered hand prosthesis was introduced in the market [4]. The last conceptual change in the prosthetic design took place when transistors came to mass production (The Russian Hand, 1960 [4]) and shortly after with the miniaturization of the actuators when the first multi-articulated fully wearable hand was designed (The Belgrade Hand, 1965 [5]).

The modern state-of-the-art commercial upper limb prostheses, though highly versatile, have a cost that is beyond the reach of many potential users. Moreover, they still require support and fitting facilities that can only be found in the highly developed regions, reducing the potential market to a small fraction. This limits industry-driven research and development that is already compromised by strict medical device legislations and requirements. Alternative commercial solutions, which are relying on less sophisticated technology, are cheaper but do not sufficiently satisfy the needs of end-users. With other constraining factors this finally amounts to high abandonment rates continuously observed over the years [6,7].

During the last decade, a new approach in the prosthetic hand design has been slowly introduced that is strongly influenced by the wide commercialization of the 3D printing technology. With these technologies, the possibility to quickly prototype a series of different designs and test them in the matter of hours at minimal costs has prompted researchers, engineers and amputee communities to look for possible solutions that could bridge the gaps in the current prosthetic market. This further yielded volunteer-driven initiatives such as e-NABLE [8] that have so far offered thousands of custom low-cost devices to amputees around the world. Furthermore, several companies [9–11] are now offering their own fully printed solutions at a fraction of the price of standard prosthetic devices.

However, though initially met with great enthusiasm by the amputee community, it should be stated that there is still no critical and systematic evidence on the actual long-term acceptance, durability, or clinical performance of the available 3D printed prosthetics. Here, we review a representative set of the available rapid prototyping solutions for each level of upper limb disability. Moreover, we discuss the current state and the future of the printed upper limb prosthetics and how they may influence the existing prosthetic market.

2. Key printing technologies and materials

3D printing is a manufacturing method available since over 30 years [12], during which a series of different techniques and materials have been progressively introduced. For prosthetic limb applications, three technologies stand out: fused

CONTACT Dario Farina d.farina@imperial.ac.uk Department of Bioengineering, Imperial College London, London, UK

deposition modeling (FDM), selective laser sintering (SLS), and polymer material jetting (PolyJet) [13]. FDM is based on semi-liquid material extrusion which is deposited in layers using a computer-guided print head (Figure 1). It requires relatively inexpensive printers and allows the quickest prototyping. However, with a deposition layer of 150 µm, it does not allow the production of precise details and the end products tend to have a rough finish (Figure 1). Moreover, since FDM requires supporting materials when printing overhanging structures, each sample needs to go through additional manual refining before completion. SLS uses heat to bind powdered materials together and to produce objects by stacking layers of powder which are then selectively fused using a laser. During the process, the non-bonded granules support the object as it is printed. Compared to FDM, it delivers smoother surfaces due to 100 µm deposition layer thickness; however, the overall production has a greater cost than FDM. PolyJet uses UV light to harden, layer by layer, a liquid photopolymer dispensed through multiple nozzles of the print head. This method of material application allows printing of several different materials in varying combinations in the same built. In addition, a deposition thickness of only 16 µm allows versatile and high-end designs. However, this is the most expensive technique and photopolymers have the tendency of degrading once exposed to sunlight [14]. All these technologies come with certain modifications that allow an increase in precision and quality of the produced prints [15], but ultimately at greater production costs.

FDM printers commonly use Acrylonitrile Butadiene Styrene (ABS) and Polylactide (PLA) filaments. Following the extensive testing [16], various versions of printable ABS thermoplastic have received Food and Drug Administration (FDA) approvals. Biocompatible and biodegradable PLAs [17] have as well received similar approvals. FDA also recognizes the SLS compatible Nylon 680 [18] and a full range of other printable materials that rely on modified versions of the available printers [19]. It is worth mentioning that there is an emerging family of rubber-based materials such as Filaflex and Thermoplastic Elastomer (Ninjaflex) that are flexible in design, high-performance, and easily printed [20]. These new filaments have already been applied for prosthetic designs [21]. Though, it should be noted that using certified materials is just the first step of the process and that the certification of the entire prosthetic systems still needs to be done.

3. Partial hand solutions

Rapid prototyping allows lightweight and versatile designs that are particularly suited for the development of small and highly tailored prosthetics for partial hand and more distal limb deficiencies. An array of custom-designed 3D printed prosthetic finger segments, fingers and partial hands (Table 1) can be found across the Internet. Origami Finger [22] (Figure 2), The Knick Finger [21], Flexible Finger [23], and early versions of PIPDriver [24] are among the best documented single finger prosthetic systems available as either do-it-yourself (DIY) solutions or as commercial products. They are built out of a range of printable materials from nylon [25] and PLA [21] to combinations of flexible and rigid plastics [21,23]. However, all these designs are easily scalable and take the full advantage of the coupled joint actuation as in their biological counterparts.

3D printed partial hand prosthetics primarily rely on body powered actuation in which the flexion/extension movement of the residual wrist or elbow is used to allow grasping (Table 1). These solutions come in a variety of designs tailored to specific user needs and they all rely on the aforementioned production techniques. One of the simplest one, Ody Hand

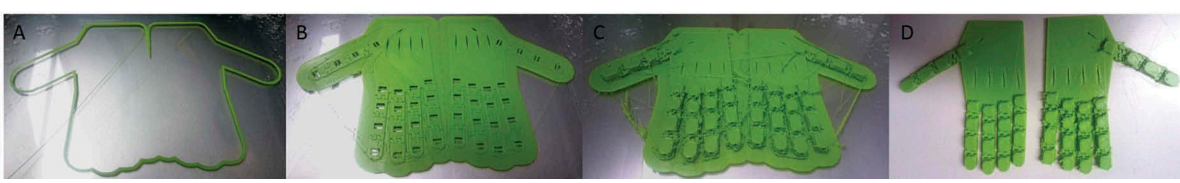

Figure 1. ProfHankD hand [64] printed on Ultimaker 2 FDM printer using 0.25 mm PLA with 30% fill. The printer head initially extruded the support raft (A) outlining the contours of the hands and helping to support the early printed structures. Layer by layer deposition takes place (B) using the sparse filling in order to keep the design lightweight and to reduce the printing time. The finished print is initially tied together by the supporting raft (C) which additionally helps removing the print from the plate without any damage. Removing excess material and polishing the edges of the print (D) takes additional time which can be as long as the print itself. Skilled work and often specialized tools are required to reach the final form of the print.

Table 1. Overview of representative 3D printed upper limb prosthetics and their features.

	Level of disability	Printing material	Actuation	Control	Unique feature
Origami Finger [25]	Finger	Nylon 618	Passive	Body powered (finger phalanx)	Compliant
Cyborg Beast [28]	Partial hand	PLA/ABS	Pretension/Cable	Body powered (wrist)	Highly robust
Flexy Hand [38]	Partial hand	Fila Flex	Pretension/Cable	Body powered (wrist)	Compliant and biomimetic
Brunel Hand [9]	Transradial/ Transcarpal	PLA	Electric Linear Actuators	EMG/IMU	CE certified
Etho Hand [49]	Transradial/ Transcarpal	ABS	DC Motors	Not defined	Ball joint motorized thumb
Andrianesis' Hand [53]	Transradial/ Transcarpal	Duraform HST	Shape Memory Alloy	EMG/FSR	SMA actuators and motorized wrist
Create Arm [66]	Transhumeral	Flexi Fit	Pretension/Cable	Body powered (shoulder)	Medical grade printing material
Robotic Arm [108]	Transhumeral	PLA	Electric Servo Motors	Not defined	High level motorized device

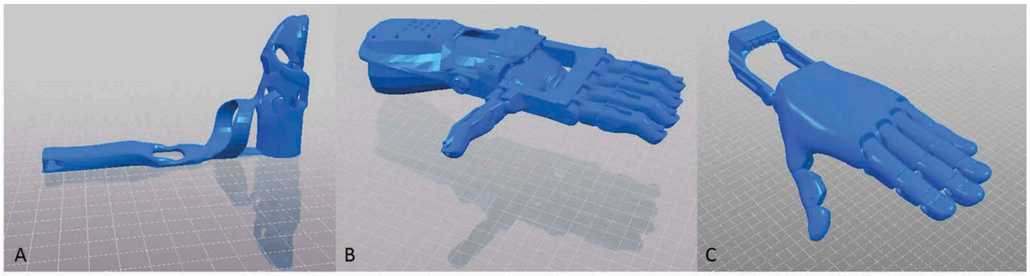

Figure 2. Complete 3D models of partial hand prosthetic solutions: Origami Finger [25] (A), Talon Hand [36] (B), and Flexy Hand [38] (C). All three devices are body powered and hence are produced with the overhanging support for the most distal joint.

[26], designed specifically for children, is printed in ABS and uses 1.2 mm nylon monofilament cables for actuation. It is produced with only two fingers and a thumb with a possibility to harness very small palms. Phoenix hand [27] and Cyborg Beast [28] are perhaps the two most prominent 3D printed prosthetic designs featuring the full set of five fingers. Cyborg Beast is the outcome of research conducted at Creighton University targeting children with partial hand deficiencies. The subsequent versions of this device resulted in an easier and more robust design. The Phoenix hand is a solution offering better aesthetics. It is available in a range of variations and overall, it is a very efficient passive device, featuring both easy printing and assembly. Its most efficient version is the Unlimbited Phoenix [29] and the most robust one is the Phoenix Reborn [30] specifically developed for users in Sierra Leone. According to the developers, the best performance of the Phoenix Reborn hand is obtained by printing it with Raise3D HK Printer with 1.75 mm extrusion printing head [31]. It comes with the wide cable tunnels and instead of usual rubber bands featured across other designs it relies on elastic cord for supporting the hand open function. In comparison to the Phoenix hand, the Raptor (Reloaded) has a more complex design that allows modification of individual parts and is envisioned as a highly personalized solution [32]. The suggested printing specification states that printing should be performed using PLA, with 0.2 mm layers and 35% infill [33]. One of the specific modifications of the Raptor hand is the Osprey hand [34] that has been optimized for the use of heavy gauge nylon monofilaments and as such it provides high grip forces. Therefore, this device does not include any additional elastic or spring elements or any other mechanical extension. On the other hand, it has poor performance when handling small objects [35]. For users who require even greater grip forces there is the Talon hand [36] (Figure 2), which is partly relying on the Osprey design. However, this prosthetic requires greater mobility of the residual wrist joint in order to be operated. While the above designs were mainly derived from functional needs, an esthetically appealing design was the main driver for the K-1 hand [37] and subsequently the Flexy hand [38]. In the K-1 hand, all the cords are recessed and there are no metal parts. Flexy hand prosthetic (Figure 2), besides having the closest resembling design to the natural hand, relies on flexible filaments also for the hinges. Effectively, this means that no elastic cords are necessary to return the fingers to their outstretched position. Furthermore the elastic actuation system does not have any rubber parts, directly decreasing the friction and force needed to operate the prosthetic [39]. Finally, stretchable tendons offer the possibility of adaptive grip for grasping irregularly shaped objects.

Each partial hand solution includes a limb attachment (Figure 2) which depends on the actuation platform, targeted function, and the number and type of joints that are affected by the disability. In general, the most distal overhanging joint is being harnessed to provide support and linkage (Table 1). There are a few proposed methods and recommendations for fitting certain solutions [28,40]; however, a systematic, large-scale report on the subject perceived comfort is still missing. Still, some of the designs do include additional padding [41,42].

4. Transcarpal and transradial solutions

DIY rapid prototyping communities have seen a significant influx of artificial hand designs over the last 10 years. However, a large number of these solutions are directed to purely robotic rather than prosthetic applications. Thus, many of them have not been tested on patients nor have even evolved beyond a table top design.

The challenge of the translation from robotics to functional prosthetics is mostly related to the mechanisms used to actuate different functions of the design. Indeed, most of the 3D printed hands include either rudimental tendon pulling or low-level and bulky actuation without any plans or solutions for compact assembly (Table 1). However, those devices that include wearable options usually come with either body powered actuation mechanisms or EMG control. Also, there are reports of hybrid systems that incorporate IMU sensor information [9] or flexion sensors [43]. Finally, there are also examples of systems under voice control [44] or control based on a combination of force sensors and light dependent resistors that activates the hand in proximity of an object [45]. Most commonly these are traditional pretension systems or electrical motor powered designs (Table 1). The latter ones rely on DC motors [46], stepper motors [47], servos [48–50] or linear actuators [9]. They are usually positioned in either the palm area [9,46,48], or in the area of the forearm [47,49,50]. In addition, there are also systems that include compressed gas actuation [51] with intrinsically flexible and responsive manipulation of objects, although these designs are bulky and noisy. On the other hand, virtually noiseless prosthetic hands have been developed using shape memory alloy (SMA) wires [52,53]. This type of actuation enclosed in a lightweight 3D printed chassis provides an interesting concept; however, the relatively weak grip loads of only 1.5 kg [53] in comparison to around 4 kg handled by the human hand [54], might limit clinical applications.

Besides the actuation methods, the differences between 3D printed hands are mainly related to the design of the wrist and the thumb. Only few wrists have been designed with a focus on prosthetic applications. The Victoria Hand [55] offers a passive rotation and flexion/extension wrist joint while the HACKberry Hand [10] also includes ulnar and radial deviation. The Andrianesis' Hand [53] is the only fully 3D printed prosthetic hand with wrist rotation which is powered by an electric (stepper) motor. Loaiza [46] proposes a battery powered rotation and flexion/extension solution, however in a rather bulky design that has been subsequently abandoned in later systems [48]. Finally, the InMoov2 hand [56] does not include an active wrist but it is compatible with a full robotic arm concept [47] which includes a wrist rotation unit. For the thumb designs, the lighter prints usually feature simple one DoF options, specifically positioned to allow either the greatest grip force or the most versatile grip operation. However, Laliberté et al. [57] proposed an under actuated thumb that allows two DoF thumb activation in a simple and lightweight manner. The Victoria Hand [55] again offers the passive joint option commonly found in the mid-level commercial prosthetics. However, a significant number of heavier printed designs offer two DoF motorized thumbs similar to those present in the state-of-the-art commercial hands [58,59]. Finally, Konnaris et al. [49] implemented a ball joint thumb design featuring three motors which drive six strings for highly dexterous in hand manipulation.

A printed hand that stands out for its innovative design is the under actuated yet highly versatile Pisa/IIT SoftHand [60]. Its design relies on only one actuator that controls 19 DoFs in 4 fingers and an opposable thumb.

The majority of designers print their artificial hands using either ABS or PLA and this is primarily due to affordable printers with large support communities. Nylon [43], Duraform HST [61], Ninjaflex [62], and composites such as DM9795 [63] have also been proposed for specific hand designs or functions. Most of the designers recommend using 20–30% body fill and layer thickness of 0.1–0.3mm in order to achieve high performance at reasonable costs and production time. Printing time varies significantly depending on the design, set parameters, printer type and size, level of customization, and the level of desired details. It ranges from several hours to several days.

Not many designs provide information on the overall weight and price of the final product. However, it can be estimated that there are noncommercial options ranging from around a hundred grams with less than 5$ of material cost [64] up to a weight of 960 g of the O'Neill hand [65] that is priced at approximately 570$. The few commercial systems available on the market have costs ranging from 1300$ (HACKberry Hand, with a weight of 750 g [10]) to 2100$ (Open Bionics Brunel Hand, 370 g [9]).

5. Above elbow solutions

As for commercial systems, there are relatively few above-elbow 3D printed prosthetics with respect to more distal devices. The Create Arm [66] offers a body powered gripper that is transhumerally fit and activated using a shoulder shrug. Both elbow and wrist joints are passive and can be manually adjusted. The wrist can alternatively be sourced from other commercial prosthetic vendors. Unlimited Tomorrow has published design instructions for their Robotic Arm [67] that comes with nine DoF motorized hand, wrist, and elbow. This prosthetic is made out of 1.75 mm PLA with 0.3 mm layer height. While fully open source, the designers do not provide any solutions for the device interfacing. Conversely, the Limbitless Arm [68], designed using Ninjaflex, includes EMG control, although the control addresses only one DoF. Similarly, the Mind Controlled Robotic Arm [69] includes an EEG-driven 1-DoF 3D printed arm system. The inMoov project extends the aforementioned hand system [47] with an actuated elbow [70] and shoulder [71], but the level of optimization that might be needed in order to convert this rather lightweight robotic solution into a wearable prosthetic is still unclear.

6. Cosmesis and sockets

With the reduced functional complexity and desire for high level of customization, prosthetic cosmesis strongly benefits of the features offered by the rapid prototyping technology. Complex and avant-garde cosmesis designs are gaining in popularity [72–74]. Companies such as Glaze Prosthetics [11] offer commercial high-end quality products addressing the different needs of their customers. The designer Evan Kuester has built a successful portfolio by 3D printing fashionable prosthetics [75–78] cosmesis for a range of clients. These devices usually employ SLS printers and as such mostly rely on Nylon and composite materials.

Similarly, sockets and prosthetic attachment systems are receiving significant attention by the 3D printing community. In combination with 3D scanning technologies, rapid and precise production of casting negatives is now commercially available [79,80]. Moreover, printing of protective covers as well as whole sockets can now be performed in <48 h [80].

7. Traditional commercial systems and alternatives

The most advanced and versatile commercial products not relying on 3D manufacturing address transradial and transcarpal impairments. Ottobock Michelangelo Hand [81], Touch Bionics iLimb [82], RSL Steeper BeBionic [83], and Vincent Evolution [84] are just some of the highly actuated commercial devices that allow the control of multiple grip patterns [58] or even of individual fingers [59,83,84]. These hands usually include passive wrist units allowing manual rotation and/or flexion/extension [82,85,86]; however, motorized rotation units are also available for some products [86–88]. These hand prosthetics weight in the range of 400–600 g, depending on the model and the available attachments [89]. Simpler, cheaper and robust prosthetic grippers are also widely offered by various vendors. Ottobock Sensor Speed Hand [86] is a market representative of this class of products. It allows an EMG-driven single DoF open/close function with forces up to 100N and an optional passive or active rotation unit. Moreover, there is a whole range of body-powered terminal devices. For example, the Large Titanium Split Hook offered by RSL Steeper [90] weights only 151 g and offers a functional opening of 124 mm.

There are fewer commercial prosthetic solutions for trans-humeral and shoulder disarticulation impairments. Manually operated and body-powered elbows dominate the market. Still, several major prosthetic brands, such as Boston Digital [91], Fillauer [92], Hosmer Dorrance Corporation [87], and Ottobock [93], do offer electrically powered, EMG-driven devices. It is expected that with the wider acceptance of Targeted Muscle Reinnervation [94] and advances in EMG control approaches [95,96], the number and functions of these units will increase. Currently, only Luke Arm offered by Mobius Bionics includes a motorized shoulder joint [97] allowing humeral rotation, and flexion/extension and adduction/abduction of the shoulder. In addition, Ottobock DynamicArm includes a shoulder harness that comes with a lockable hinge mechanism to increase the range of motion [93].

The majority of commercial devices are provided to patients together with a professional prosthetic fitting service by certified orthopedic technicians. Fitting includes customized molding and productions of the sockets which usually takes several sessions in order to achieve optimal comfort and function. Modern sockets are made out of composite materials with soft silicon or rubber liners that allow an intimate fit in a hygienic and easily interchangeable form [98]. Higher level amputations may involve different type of harnesses that in addition to providing support for the prosthesis may include the mechanism for body powered actuation of the joints.

All commercial products adhere to either CE or FDA regulations and are provided with the extensive guarantees and support across the markets. Almost all products are sold exclusively through certified dealers which include professional servicing and fitting. Depending on the region, a selection of the market-specific commercial devices is supported through the local healthcare systems.

8. Expert commentary

3D printing technology is an emerging trend that has not yet found its clear place in the slowly changing market of upper limb prosthetics. The eagerness and wide acceptance of the amputee population of the rapidly prototyped prosthetics, judging by the global presence of specialized shops offering support to the 3D printed prosthetic users [99], is a strong indicator that there is a necessity for lightweight, highly customizable, and overall affordable systems. Moreover, the cheap production costs [64,65] make these technologies attractive for large-scale prosthetic solutions in low income countries. However, the lack of systematic and long-term evaluation prevents us from concluding whether 3D printing can overcome all the challenges imposed by prosthetic applications. Furthermore, the insufficient data on the performance and user experience makes it difficult to predict whether there will soon be a structured certification track to allow for wider commercialization. Finally, this lack of data prevents from assessing whether the large-scale production of the 3D printed limbs is a sustainable business option or whether the complexity and the lengthy production time will prevent mass manufacturing.

Low price tag of the printed prosthetics is something that has definitely helped promoting the technology. Though, most of the reports do not account for the costs in addition to fabrication that commercial products are required to cover. Among others, these include the costs of the design, certification, guarantee, quality control, and professional fitting. Certification alone is a process that can take years and requires substantial funds for running all the necessary tests. The costs of guarantee and professional fitting are the expenses directly reflecting on the price of each unit. These are often being neglected when costs of 3D printed limbs are calculated yet are essential expenditures for securing the optimal performance of the system. Moreover, it is quite common that some of the 3D printed parts need to be rebuilt, even when made with established processes, due to common technology problems which prolong the building process. In addition, following the printing, sometimes an elaborate manual refining of the components is needed (Figure 1) and the assembly can be a delicate and lengthy process depending on the complexity of the system. Still, for a low-scale production of highly customizable products, the overall costs can be significantly lower than those of commercial counterparts.

Based on the preliminary reports, low grip strength and fragile structure might still prevent 3D printed prosthetics to significantly compromise the conventional prosthetic market. Vendors of the most popular commercial hand prosthetic systems are well aware of the importance of these two features. Accordingly, they are designing their devices to deliver two or even three times higher forces (70–140N [89]) than the average biological hand is able to exert (men: 46N, women: 30N [54]). Commercial prosthetic hands on average require 0.21 repairs per year [100] with myoelectric devices needing maintenance only 0.19 times a year [100]. However, these rates of repair are already too high for the most committed users [101]. Robustness and grip strength may be the most relevant drawbacks preventing 3D printed hands to become the primary prosthetic solutions.

9. Five-year view

With the reduced complexity, and strong need for lightweight and highly tailored solutions, partial hand prosthetics are a portion of the market that may substantially benefit from the 3D printing technology. Due to the nature of the deficiency, these prosthetics can be easily coupled with joints of the most distally available anatomy allowing simple yet effective body powered control. Given the opportunity for a flexible design, this can result in an intimate fit and eventually deliver sufficient grip force for increased functionality. The initial reports [28,102] on the performance of partial hand prosthetics target primarily the young population. This is an indicator of unmet need, but also of the user group that might be more prone to accept and eventually benefit from this technology.

A market in which 3D printing might also flourish is that of prosthetics for children and young adults. This market sector is currently not well served, mainly due to the need for high customization and progressive design changes to match the users' development. Current devices are rather expensive [100,103] and the effort needed for continuous customization is significant. Moreover, these systems are currently simply a scaled down version of standard devices without specific considerations for the rapidly changing anatomy [104,105]. This can potentially further tamper the already fragile psychological state of child prosthetic users [106,107]. 3D printed prosthetics might offer a functional and engaging option that may ensure a sound transition to the established commercial devices in later age.

Easily adjustable and highly customizable, printed prosthetics might further expand the market of training prosthetics. Being low-cost, they could easily provide new users with different configurations and control options that would not only help them to select the optimal device for their needs, but also aid the overall rehabilitation process.

A shift toward increased number of components being 3D printed, and the fusion of this and other manufacturing techniques is already taking place and can be expected to expand. Since the cost of socket production is currently low and current sockets offer high comfort, it is unlikely that there will be significant influence of 3D printing technology in the socket production industry. However, due to robustness being less of a priority, prosthetic cosmetic enhancements and cosmesis in general might benefit from the versatile 3D printing possibilities.

Key issues

- 3D printed prosthetics are suffering from essentially fragile design
- These systems are on average having low grip (joint) forces
- There is still no longitudinal data on the actual usability of the devices
- Current manufacturing process requires time and significant manual work, and as such the efficacy of the large-scale production is debatable
- Just a few devices have received certification and as such there is still no established pathway for full CE marking or FDA recognition

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