Human Aspects of Advanced Manufacturing, Vol. 80, 2023, 236–244
https://doi.org/10.54941/ahfe1003526

The Contribution of Additive Manufacturing in the Design of Inclusive Prostheses

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ABSTRACT

One of the main means through which people with severe physical impairments can enhance their quality of life is through prostheses. However, traditional design and manufacturing techniques mainly tied to conventional industrial technologies used in the creation of prostheses limit the opportunity of people to fully enjoy enabling solutions when transposed into everyday life situations. The use of socially inclusive design approaches and innovative 3D Printing technologies could help designers creating inclusive solutions that improve the quality of life of all users, whilst reducing the social stigma associated with having a prosthetic body part. Accordingly, designers can significantly contribute to reducing negative impacts resulting from the use of such solutions. This study examines the inclusive design and manufacturing of inclusive prostheses using 3D Printing technologies, as well as enabling topics for design advancements and positive effects on the user experience of people with physical impairments. This study shows how the combination of Inclusive Design and AM benefits the creation of enabling prostheses in an innovative and more socially oriented way.

Keywords: Inclusive design, 3D printing, Prostheses, Design innovation

INTRODUCTION

According to the World Health Organization (WHO), the global number of people who require prosthic services is estimated at 35–40 million, and this demand is increasing due to a range of factors, both societal and medical (WHO, 2017). For many users, living with a prosthesis can be difficult, humiliating, and sometimes psychologically and socially painful. Besides, the public opinion considers artificial body parts just as needed medical equipment with the primary function to compensate the missing human's functionality due to physical alterations. The design of prostheses represents an emerging market that requires both technological and medical improvements to benefit users from the use suitable products, though more social exploration into impacts are needed.

Within a social perspective, recent studies into the design and manufacturing of prostheses offer opportunities to project this field of study into a more inclusive dimension by including Inclusive Design. Traditional concepts on designing for inclusion simply suggest to design for the widest possible population (Clarkson et al, 2015); however, Inclusive Design is a much more complex domain not only related to the physical dimension (Bendixen and Benktzon, 2015; Bianchin and Heylighen, 2018). The inclusive design of prostheses can force designers to embrace a more holistic angle when approaching users that will benefit from a functional object for the rest of their life. Accordingly, the mere 'empathy-driven design of medical solution' is no longer the sole approach that can be used to provide normality into people's life. Enabling people to live pleasantly in a living ecosystem (Sanders and McCormick, 1992) while they feel respected and fully integrated is paramount.

Advances in the field of 3D Printing offer opportunities for rethinking the ways designers and medical teams conceive medical solutions for people (i.e., Cabibihan et al., 2018). Beyond methodological and procedural improvements offered by technical developments such as flexibility, affordability, development of complex geometries, etc. (Kate et al., 2017), 3D printing can also stimulate deeper reflections on producing cultural advances in the creation of artificial body parts. In other words, using 3D Printing only to speed up or to make rational the manufacturing process risks to fail in intercepting the latent demand of inclusive solutions required by users, and for which traditional manufacturing processes cannot provide effective answers.

Examinations around the inclusive design-oriented factors behind the creation of enabling prostheses made using 3D Printing technologies is presented in this work. Discussions and considerations on early relevant topics identified to produce positive – re: more inclusive – effects on the user experience of final users that demand for innovative prostheses are provided throughout the work.

ANALYSIS OF METHODS USED FOR THE REALIZATION OF PROSTHESES

Impairments in localised body parts can be related to many distressing episodes, which can be both congenital aspects (i.e., cancer and diabetes) or external factors (e.g., trauma). These can necessitate the amputation of body parts resulting in distressing conditions for people when performing even basic daily routines. The creation of bespoke prostheses helping people to reduce distressing experiences follows, in principle, a codesign-led process involving many skills and professionals, including designers and people that will benefit from them – see Bespoke Bodies (2020) and Williamson (2020). Designing and producing effective solutions for impaired people needs using 3D Printing produces improvements. This section provides evidence on the general process used to design prosthetics, along with a simplified analysis of the AM-based method for implementing artificial body parts.

General Process for Designing Prostheses

The process of creating bespoke prostheses does not only concern the design and manufacturing stages (Joannes et al., 2011), but also design aspects and participatory research methods that consider psychological aspects like acceptance and sociological ones like training in daily use. The process related to the design and manufacturing of prosthetics can synthetically be described as follow (generally deduced from Joannes et al., 2011; Tryggvason et al., 2017):

Stage 1 – Relevant anthropometric and biomechanics parameters are extracted from people needing of a prosthesis to equilibrate body functionalities. This is the *"Data Extraction"* stage. Depending on the part of the body to replicate, the identification of human data considers the residual body part to which integrate the prosthesis, its residual functionality, the complexity of movements to perform, as well as aesthetics to reduce the social stigma. Mixed methods can be used to identify relevant aspects for the later stages.

Stage 2 – Data extracted from user are processed in the *"Modelling"* stage. The modelling process aims at replicating the missing body part to provide users an equilibrate solution to be pleasantly used every day, unless the prosthesis is used for specific tasks like sport activities or similar. The digital modelling for rapid prototyping provide cost-effective solutions for users to assess early feedback and to record initial insights for later refinements.

Stage 3 – The *"Prototyping"* stage is important to translate previous information into three-dimensional functional artefacts for early user interaction and simulations. Mechanical functionalities, electronic equipment and mechanisms are tested by involving users into the process; this to assess the congruity of the prothesis in relations to users' expectations and daily tasks. Corrections and adjustments in functionalities often occur to better comply with user expectations.

Stage 4 – The *"Final Production"* of the prosthesis happens when both users and medical team agree with the product refined through iterative sessions. At this point, users are also trained on how to use it and how to run daily maintenance (i.e., in the case of simple electrically powered prostheses). The autonomous use is also important to provide users independency and autonomy when performing daily activities.

AM-Based Method for Designing Prostheses

The design and production of prostheses can benefit from a number of advantages provided by 3D printing processes (He et al., 2014). For example, a generic socket model can be created around the user's remaining body part by simply using a 3D scanner that later be merged in a more comprehensive CAD environment. In this way, it is possible to immediately print and test the socket to ensure that it is secure and comfortable on the residual body part, as well as to locate electric sensors usually employed to coordinate movements (Tong et al., 2019). CAD files can be modified after the necessary alterations are made or by altering the proportions to fit the user's physique. Such innovations produce a process harmonisation and reduction of processing times.

When compared to conventional manufacturing methods, 3D Printing considerably accelerates the process of producing a prosthesis. The use of a 3D scanner speeds up the process of creating an accurate representation of the remaining body part, providing more accurate data for digital processing and replication (ten Kate, 2017). The printed prosthesis can be manufactured in any shade required by simply using a 3D printer and a wide array of materials, whether it matches skin tone or a different colour. For example, this approach further eliminates the inconvenience and distress associated with getting a prosthesis for children who do not wish to undergo an expensive and time-consuming treatment every two years. Before it is printed, the amputee can alter the prosthetic's design to make it as a natural extension of themselves – discussed by Arabian et al. (2016).

THE SOCIAL RELEVANCE OF DESIGNING FOR DISABLED USERS

Previous sections show the product-led design and manufacturing process used to make medical prostheses. However, the acceptance of medical devices is an important social issue to consider when designing such products for an user (Pullin, 1964), as for many of them prostheses will be tools to be used for years. In fact, they allow users to take part in a subset of rituals that are part of the natural process of societal inclusion. It can be deduced that prostheses are products having a twofold nature: (i) a functionalistic nature, mainly tied to restoring the functioning of missing body parts, and (ii) a social nature, which related to the way people can feel themselves included in their living ecosystem.

In western culture, prostheses can help people feel less isolated. Their use can help people with disabilities to have a more positive body image and lessen perceived social stigma by preventing exclusive conditions deriving from cultural biases (Murray, 2005). Early prosthetic fitting is therefore crucial to improving the chances of effective rehabilitation and enhancing amputees' enjoyment of their prosthesis. Positive thinking is encouraged by focusing on the potential for future functionality with a prosthetic device rather than on the limb loss; concepts like normality, naturality, comfort, uniformity and autonomy are therefore crucial.

Receiving a prosthesis can go more quickly with the use of 3D printing, enabling quicker rehabilitation and enhancing long-term uptake. Furthermore, when working for disabled people, designers[1] must show higher empathy and sensitivity in dealing with complex aspects that often are hard to grasp. These include, but not limited to, (i) the social stigma related to the design of medical objects; (ii) the potential negative idea (e.g., compassion) often associated to disabled people when using a medical device; (iii) the psychological perception of the sense of normality compared to the contextual factors; (iv) fashion issues; (v) understanding the will of disabled people to have self-confidence.

The use of a socially oriented codesign process to design and implement enabling and inclusive 3D printed prostheses make users able to be empowered by the ability to have a body part that is fully customized and tailored on their needs, even new ones that cannot be achieved by using traditional manufacturing techniques, improving usability and flexibility, as well as

[1] The term designer is here used in a broader sense to describe anyone involved in the design and manufacturing of prosthetics, regardless the fact if he/she is a product designer of a technician that work for a medical team.

social acceptance and inclusion. When properly applied through a socially inclusive angle, prostheses stimulate amputees to learn and get confidence in dealing with daily situations. Thus, with the aid of 3D printing, the stigma associated with prosthesis can be readily eradicated by removing the shame caused by the use of unsightly medical models.

According to studies in the field, wearing an inclusive prosthesis – an artefact codesigned with final users, made following their needs and social wishes that goes beyond the mere design process related to the creation of a medical product –may help people to feel reintegrated into society, promoting positive body images (Mireille & Foje, 2019). Thanks to a social-led design practice and the use of 3D Printing, more amputees can wear prostheses that ultimately improve mental health and social conditions.

TOPICS AND SOCIAL LENSES FOR THE INCLUSIVE DESIGN OF 3D PRINTABLE PROSTHESES

Literature review and data comparisons performed against relevant case studies provided evidence and guidance for the creation of a set of design recommendations to improve the social acceptance of prostheses by combining inclusive design approaches and 3D Printing technologies. Findings are synthetically discussed below in relation to main topics emerged.

Enabling Aesthetics

Aesthetics is crucial for the social acceptance of prostheses, especially when related to new users. Design in the perspective of normalisation and uniformity of shapes helps users accepting the medical device by reducing the social barriers of using a medical tool (Mireille & Foje, 2019). Aesthetical factors can be improved by the smart use of 3D printed when new visual standards are introduced into medical domain. This further elevates the visual quality of prosthetics getting closer medical domain and fashion. Texture, visual and haptic patterns, colour variations brings originality and personality whilst transposing users' ethos and empathy into design process. Inclusive-oriented design process must consider user needs and wishes by interpreting aesthetical qualities in relation to harmonisation of proportions and silhouettes. Interviews with users, user trials, need analysis and other qualitative methods help designers in maximising the inclusive design and manufacturing processes.

Fashion

For some users, fashion is an important key driving force for improving the social acceptance of prostheses, which recall tribalism, social acceptance and sense of belonging – re: moving from what I wear to what I am (product-centric approach VS user-oriented design) (Shah et al., 2014). Fashion is also an important social asset to stress when translating qualitative insights deduced in the codesign process, when designers are essentially asked to identity meaningful values to be used in the characterisation of prosthetics' aesthetics. Focused codesign methodologies should be used to enrich the inclusive-oriented design process with empathy-driven insights.

Customisations

The flexibility in the modelling and manufacturing of 3D printed solutions offer opportunities to operate prosthetics personalisation (Simon, 2021). This is echoed by studies in the field of Design for Sustainable Behaviour that demonstrate the higher empathy generated in the user-product interaction foster personalisation and the opportunity to add qualitative insights useful to better explore modalities through with users interact with the surrounding environment. This produces a twofold effect: (i) the extension of product's life-cycle – an artefact lasts longer than ones considered only for their performance (re durability, extension of the product life, etc.); (ii) users are more keen to actively contribute in supporting the customisations by sharing their experience, which mirrors in emulations. Combinations between Design for Sustainability and Inclusive Design are recommended to elevates the quality of inclusive prostheses toward sociological dimensions.

Multisensory Qualities

Humans experience the world through synesthetic perception, and this aspect when properly integrated into the co-design process, can be brought in the design and manufacturing of 3D printed inclusive prostheses. Multisensory stimuli help users in reducing the negative psychophysical and social perception of living with a medical device, which collaterally helps the mitigation of social exclusion and stigmas. Hearing, haptic, olfactory stimulations can easily be replicated through AM technologies and novel materials. A sensory-oriented design approach allows designers using novel design requirements useful to generate inclusive codesign processes as well as the production of enabling objects, going beyond the mere manufacturing of a medical object.

Durability

Replacement over time is one of the main limitations related to the use of prosthetics. But this aspect is also valid for all industrial products when it come sustainability. Data demonstrates that adults replace their prostheses every five years, whilst children reduce this period to every two years. In a global perspective, this can be a time-consuming and unaffordable practice both for users and the national health systems. Although medical advances allow to slightly reduce the need of frequent replacements, this operation still demands a lot of time and attention to attain the desired effect. Extending the durability of prostheses helps users in establishing stronger empathies and affections with the products – and this is a key value for Inclusive Design. This also generates normalisation in aesthetics, shapes and functionality. An inclusive design approach for the creation of 3D printed prostheses should promote the disassembly of parts to replace, including skins, so that benefits can occur even on the side of sustainable production.

Inclusive Processes

Involving final users in the codesign of prostheses offer opportunities to reinforce the cooperation and the trust into medical sector and staff involved in the production of medical devices. This is indeed the baseline for any inclusive design intervention. However, users cannot only act as passive players of the process (re people receiving an artificial body part). They indeed can bring interesting insights that can significantly refine the way designers and technical staff produce the artificial body parts. A deeper involvement of users throughout the whole process – research, design, manufacturing – makes them more integrated and part of the creation stages, exalting the sense of pride when making a product for themselves, that eventually can benefit other users too (Enabling the Future, 2020). This can also be transposed into manufacturing processes, when users can directly suggest strategies for product personalisation and improvement. A more structured inclusion of final users can therefore enrich the whole process of participation over all development stages.

Affordability

Affordability has been recognised as one of the main barriers in accessing high-quality prostheses, and in general it perfectly meets inclusive design practices. Even the most performing prostheses, when too expensive, can be considered as an 'exclusive solution'. For example, depending on the configuration required and the desired level of dexterity needed by the user, the cost of bionic hands traditionally made without the use of 3D Printing technologies today can range from $20,000 to $100,000 (Disability Horizons, 2021). Accordingly, the affordability of solutions is one of the primary elements to consider when designing and implementing a solution like prostheses. 3D Printing technologies can reduce the barrier in accessing basic services as well as triggering complementary business models that may be very effective in a sustainable perspective of distributed manufacturing, or even raw manufacturing in emerging and developing countries. Placing the 3D Printing process in a socio-economic perspective reinforces sustainability and inclusivity qualities.

Sustainable Materials

New materials like eco-materials, bioplastics, and recycled semi-finished materials support the 3D Printing processes for inclusive prostheses by offering opportunities to improve the ecological sides of studies on the design of inclusive medical solutions (Debnath et al., 2021). A convergence between sustainable design and inclusive-oriented research explorations are recommended when it comes materials. Therefore, the use of local resources within sustainable productions may help local productions to contribute the medical sector – impacts on socially sustainable businesses. In a socio-economic perspective, this aspect can also open up to the diversification of business models of companies that work with semi-finished products and materials.

Playfulness

If the sense of normality, harmony in the proportions, and functionality are key design priorities for adult users, these qualities can be less relevant in the design of prostheses for children. For example, the UK based company Open Bionics offers users the opportunity to integrate a wide range of swappable magnetic covers for children prostheses (Open Bionics, 2018; 2020). This improves aesthetics and can be changed to fit mood or outfit. Panels are inspired by superheroes and other fictional characters, or more simple panels in a variety of colours and textures. This design strategy is highly inclusive and offer users the opportunity for individualisation.

Imperfections

The grade of flexibility, precision, and personalisation introduced by 3D Printing processes in the production of small-scale products can be a mean to radically rethink the sense of perfection of a medical product. Traditional semiotics patterns may be used even to give users the opportunity to introduce little details like "designed imperfections", which would move into ideas of unicity. If from one side the idea of perfection restores the latent perception of normality – in general symmetries and rationalisation are favoured – for users forced to live with a prosthetics, 'agreed anomalies' may produce empathy and an idea of naturality. Besides, the idea of introducing controlled imperfections is not new in nature – e.g., skin moles – 3D Printing processes may help people to ideate own imperfections to deliberately alter the sense of aseptic perfection typically linked to medical silhouettes.

CONCLUSION

This work provided early considerations and reflections on emerging possibility deriving from the inclusion of socially inclusive design lens into the design of prostheses for all users. Specifically, synergies and topics for new design research avenues linking Inclusive Design and 3D Printing have been discusses.

Topics and social lenses for the inclusive design of 3D printable prostheses, made produced through the comparison of case studies against relevant literature in the field, suggest to integrate the Inclusive Design approach since the beginning of the development stages, where codesign processes can maximise the extraction of useful qualitative and quantitative data from users. Such perspective can also propose personalisation and the development of innovative solutions in a later stage, contributing to mitigate the social stigma and the users' perception to live with a medical product that is just functional.

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