

Review

An Interdisciplinary Approach and Advanced Techniques for Enhanced 3D-Printed Upper Limb Prosthetic Socket Design: A Literature Review

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Abstract: This review investigates the opportunities and challenges of interdisciplinary research in upper limb prosthetic (ULP) socket design and manufacturing, which is crucial for improving the lives of individuals with limb loss. By integrating various disciplines, such as engineering, materials science, biomechanics, and health care, with emerging technologies such as 3D printing, artificial intelligence (AI), and virtual reality (VR), interdisciplinary collaboration can foster innovative solutions tailored to users' diverse needs. Despite the immense potential, interdisciplinary research faces challenges in effective communication, collaboration, and evaluation. This review analyses pertinent case studies and discusses the implications of interdisciplinary research, emphasizing the importance of fostering a shared understanding, open communication, and institutional innovation. By examining technological advancements, user satisfaction, and prosthetic device usage in various interdisciplinary research examples, invaluable insights and direction for researchers and professionals seeking to contribute to this transformative field are provided. Addressing the challenges and capitalizing on the opportunities offered by interdisciplinary research can significantly improve upper limb prosthetic socket design and manufacturing, ultimately enhancing the quality of life for users worldwide.



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Keywords: interdisciplinary research; upper limb prosthetic; socket design; 3D printing

1. Introduction

The advancement of technology and interdisciplinary research in recent years has paved the way for significant opportunities and challenges in diverse fields, particularly in the domain of upper limb prosthetic socket design and manufacturing. Prosthetic devices play a crucial role in enhancing the quality of life for individuals with limb loss, and developing personalized, comfortable, and efficient prosthetics is essential for addressing the diverse needs of these users [1]. The marriage of various disciplines, such as engineering, materials science, biomechanics, and health care, has the potential to foster innovative solutions tailored to the needs of the users [2]. However, interdisciplinary research also poses unique challenges pertaining to effective communication, collaboration, and evaluation [3,4].

This review aims to analyse the opportunities and challenges associated with interdisciplinary research in the realm of upper limb prosthetic socket design and manufacturing and explore influential instances where interdisciplinary collaborations have yielded ground-breaking developments in the field. By delving into the realm of 3D printing, artificial intelligence (AI), virtual reality (VR), as well as investigations pertaining to patient satisfaction and prosthetic device usage, this review describes potential avenues for interdisciplinary research in this field. Furthermore, it emphasizes the significance of developing a shared understanding, fostering communication, and promoting institutional innovation for successful interdisciplinary research endeavours [5,6].

The potential for innovation through interdisciplinary collaboration, particularly in the realm of ULP socket design and manufacturing, is immense. By integrating diverse disciplines, researchers can create novel solutions that address various user needs, preferences, and expectations [6]. Furthermore, incorporating advanced technological developments, such as AI and VR, opens up new research opportunities that can transform prosthetic device development and improve the lives of the users [7]. However, the challenges of interdisciplinary research necessitate continuous dialogue, shared understanding, and accommodating institutional innovation in order to optimize the collaborative research efforts [3,8].

In an era where interdisciplinary research is gaining more prominence, this review endeavours to present a comprehensive examination of the opportunities and challenges that abound within the field of upper limb prosthetic socket design and manufacturing. By addressing communication, collaboration, and evaluation challenges, and capitalizing on the innovative opportunities presented by interdisciplinary research, researchers can contribute significantly to the realm of upper limb prosthetic socket design, ultimately improving the lives of users worldwide. Through the examination of specific case studies and discussions surrounding the advantages and drawbacks associated with interdisciplinary research, this review provides invaluable insights for researchers and professionals seeking to contribute to this transformative field.

In this review, a bibliometric analysis approach was employed, utilizing Connected Papers as a citation analysis tool. This review focused on three recent and influential studies in the field of 3D-printed upper limb prosthetic sockets: Olsen et al.'s study, "3D-Printing and Upper-Limb Prosthetic Sockets: Promises and Pitfalls" [9] (Figure 1), Barrios-Muriel et al.'s review, "Advances in Orthotic and Prosthetic Manufacturing: A Technology Review" [10] (Figure 2) and Binedell and Subburaj's study "Design for Additive Manufacturing of Prosthetic and Orthotic Devices" in "Revolutions in Product Design for Healthcare" [11] (Figure 3). These studies were used as seed papers to identify essential literature in the area. Connected Papers is a powerful tool for conducting literature reviews and bibliometric analyses. It provides a visualization of relationships among papers, authors, and keywords, enabling researchers to prioritize essential texts for further exploration. Additionally, the tool is capable of organizing research papers in a visual network based on their citations, conflicts, and supporting concepts. To complement the use of Connected Papers, the authors conducted a literature search using Scite, Google Scholar, and Google Search to identify key texts in the field. Scite is a citation analysis tool for determining the reliability of research results and identifying influential research. By utilizing citation analysis, Scite determines the extent of support or opposition to particular research results.

The purpose of this review is to delineate the principal themes and evaluate pertinent academic works related to the domain of 3D printing in upper limb prosthetic (ULP) design. This includes an exploration of interdisciplinary methodologies and diverse techniques, thus facilitating a comprehensive understanding of this emerging field for researchers new to this area of study. By synthesising a range of reviews and academic papers on this subject, this review aims to accelerate the access to and assimilation of relevant research in this field.

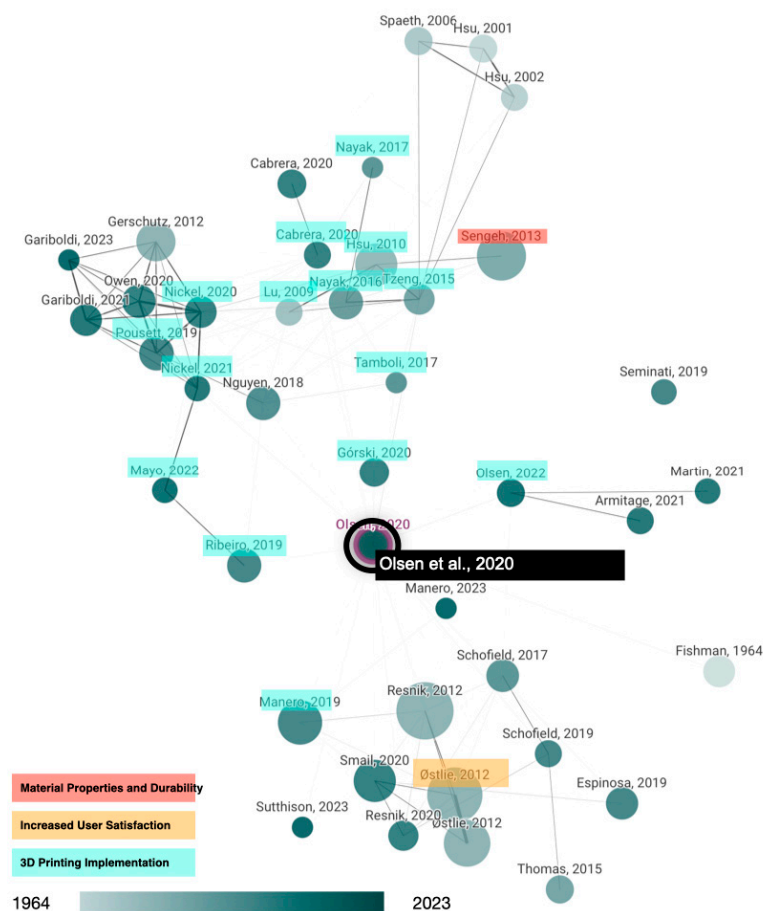


Figure 1. Prior works, derivative works of Olsen et al.'s study, and their connections. Generated using Connected Papers and edited by the author for readability.

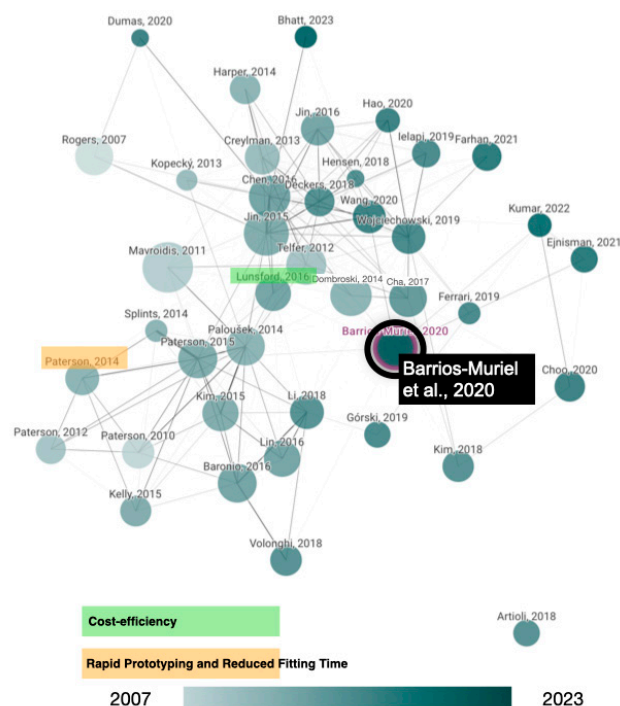


Figure 2. Prior works, derivative works of Barrios-Muriel et al.'s review, and their connections. Generated using Connected Papers and edited by the author for readability.

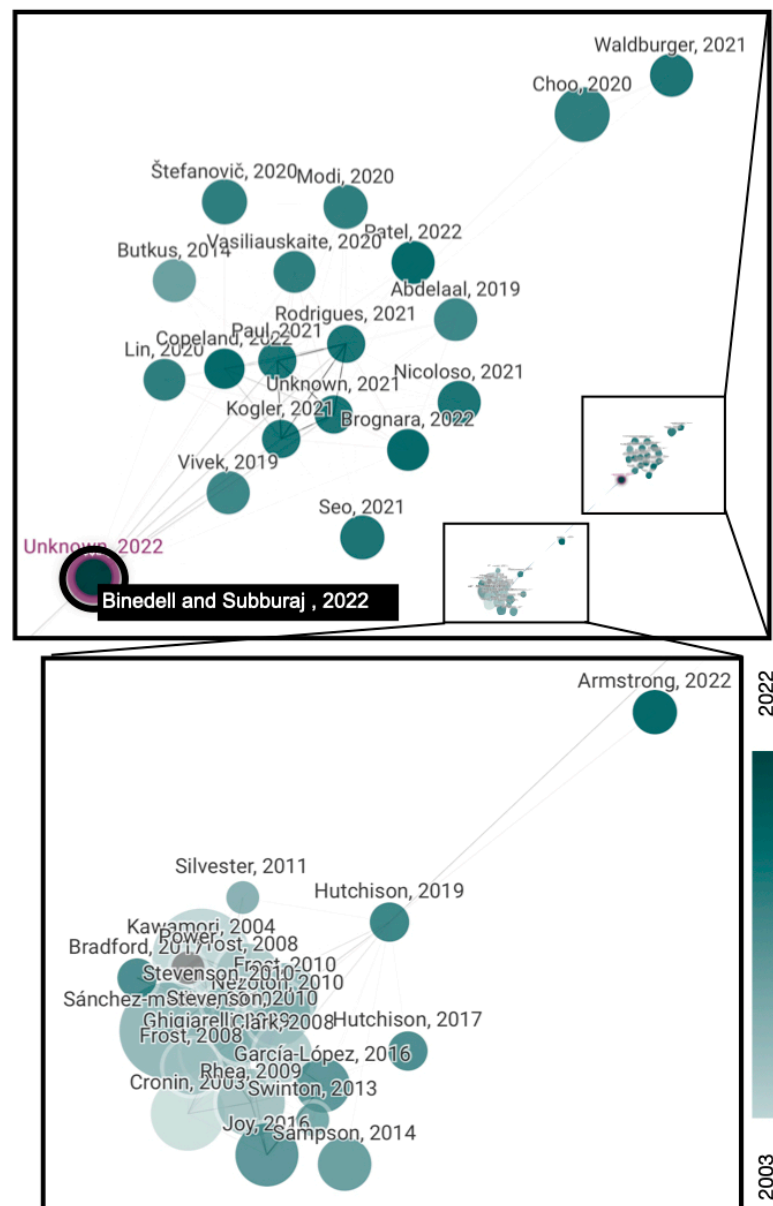


Figure 3. Prior works, derivative works of Binedell and Subburaj's study, and their connections. Generated using Connected Papers and edited by the author for readability.

2. Background on Upper Limb Prosthetics Socket Design and Manufacturing

2.1. Importance of ULP Socket Design and Manufacturing

Upper limb prosthetics (ULP) have a significant impact on the lives of individuals with limb loss or congenital limb deficiencies by restoring function, enabling participation in activities of daily living, and enhancing overall quality of life.

A critical component of ULP is the socket design and manufacturing process, which directly influences the comfort, stability, and overall user satisfaction [12,13].

The socket serves as the crucial interface between the residual limb and the prosthetic device, allowing for effective force transmission, proprioceptive feedback, and facilitating prosthetic control during various tasks [14]. An ill-fitting socket can lead to skin irritation, pain, and reduced prosthetic use, ultimately diminishing the benefits gained from wearing the device [12].

User satisfaction surveys have highlighted the importance of a comfortable and well-fitting socket, identifying factors essential for achieving a successful prosthetic fit [13,14].

These factors include the shape and size of the residual limb, the biomechanical relationship between the socket and the limb, the materials employed in socket fabrication, and the methods used to manufacture the socket [12].

Recent technological advancements have the potential to improve socket design and manufacturing by employing digital scanning systems, computer-aided design (CAD) software, and additive manufacturing techniques, ultimately leading to a more customized and precise socket fit [10,12].

With no single factor contributing more to user satisfaction than a well-fitting socket, continued advancements in this area are crucial for optimizing the use and acceptance of ULP [12].

2.2. Traditional Methods and Limitations

Traditional methods of upper limb prosthetics have evolved significantly, with early solutions such as iron prostheses used in battles being replaced with body-powered prostheses and more advanced myoelectric devices [15].

However, despite these advancements, there remain several limitations and challenges associated with the adoption and use of these devices. Body-powered prostheses have served as a crucial stepping stone in the evolution of ULP, offering a greater degree of control and dexterity compared to iron prostheses [15–17].

Nonetheless, due to the utilization of cable systems in controlling body-powered devices, these apparatuses could present challenges in manoeuvrability and restrict the extent of movement. Additionally, these devices often failed to provide the desired level of dexterity and sensory feedback for the user, leading to reduced satisfaction and usage [17,18]. While these devices have improved functionality for many amputees, they are often associated with limited grip strength, cumbersome design, and an inability to perform intricate tasks [15].

The advent of myoelectric prostheses marked a significant shift in ULP, with electromyographic signals from residual muscles being used to control the prosthetic device [16,18]. Myoelectric devices offer enhanced functionality and an improved aesthetic appearance; however, they are accompanied by their own set of limitations. Myoelectric prostheses are often costly, have limited battery life, and can be challenging to operate for some users [17].

Internet surveys of myoelectric prosthetic users have provided valuable insights into their experiences and preferences while highlighting the need to address these limitations [17]. Users have expressed a desire for improved grip force, dexterity, sensory feedback, maintenance, and durability in future devices [17].

Technological advancements such as the development of the Southampton Hand, an intelligent myoelectric prosthesis with embedded sensors, have made significant strides towards addressing these limitations [16].

However, there remains a continued need for research and development in this area to overcome remaining challenges.

In conclusion, while traditional methods of ULP have provided valuable solutions for amputees, limitations still exist surrounding device functionality, usability, and user satisfaction. Continued advancements in socket design and manufacturing, as well as new innovative solutions, such as targeted reinnervation and hand transplantation, are needed to further improve the quality of life for amputees and maximize the benefits of ULP [15,18].

3. Advantages, Limitations and Challenges in a 3D Printing Focused Approach

3.1. Advantages of 3D Printing in ULP Socket Design and Manufacturing

3D printing has emerged as a revolutionary technology with significant potential in the field of upper limb prosthetics (ULP) socket design and manufacturing. This technology has demonstrated numerous advantages, which include customization and personalization,

rapid prototyping and reduced fitting time, cost-effectiveness, material efficiency, material selection, collaboration and knowledge sharing, accessibility, and remote fabrication.

3.1.1. Customization and Personalization

3D printing offers significant advantages in the personalization and customization of upper limb prosthetic (ULP) sockets, driven by the application of additive manufacturing. This technology enables the creation of patient-specific prosthetic sockets and their components, based on individual patient needs [19,20]. This level of customization allows prosthetists to tailor prosthetics according to the unique anatomical features of each user, ensuring better comfort and functionality [21]. Consequently, such personalized and customized devices lead to improved user satisfaction and prosthetic performance [1].

3.1.2. Rapid Prototyping and Reduced Fitting Time

3D printing technology allows for rapid prototyping, which streamlines the design iteration process and promotes efficient adjustments, ultimately reducing fitting time [10,19]. This technology enables rapid ideas-to-end product transformations, resulting in a faster delivery of tailored prosthetic devices to the end-users [1]. Through such expedited prototyping, the overall time required to reach a functional and comfortable fit is significantly minimized, enhancing both the design and development process.

3.1.3. Cost-Effectiveness and Material Efficiency

Cost-Effectiveness and Material Efficiency in ULP Socket Manufacturing: Utilizing 3D printing technology for manufacturing upper limb prosthetic (ULP) sockets has proven to be cost-effective compared to traditional manufacturing methods [9,22]. Additive manufacturing requires fewer materials and components, resulting in material efficiency that leads to reduced expenses for both manufacturers and end-users [20]. This material efficiency has the potential to make prosthetic devices more economically feasible for a broader range of patients. Furthermore, accessibility to low-cost, 3D-printed prosthetic components fosters an inclusive approach to prosthetics, aiding users in overcoming financial barriers [21].

3.1.4. Material Selection

The application of 3D printing in upper limb prosthetic (ULP) socket design has expanded the available material options, allowing for greater customization to best suit the needs of individual patients [20,23]. Advanced materials, such as thermoplastics, composites, and resins, can be chosen based on their mechanical properties, biocompatibility, and resistance to wear and tear [24]. These materials can be used for manufacturing the socket and its components, ensuring optimal performance, longevity of the prosthetic device, enhanced comfort, and providing increased customization options [10].

3.1.5. Collaboration and Knowledge Sharing

The nature of 3D printing technology fosters collaboration and knowledge sharing among various stakeholders, including clinicians, researchers, engineers, and users [1,25,26]. The accessible nature of the technology facilitates the sharing of design files, research data, and learnings, ultimately promoting the development of more effective prosthetic designs [20]. This rich, collaborative environment leads to improved prosthetic designs and increased innovation in upper limb prosthetic (ULP) socket development, benefiting prosthetic users worldwide.

3.1.6. Accessibility and Remote Fabrication

The ability to share 3D design files digitally, coupled with the adoption of 3D printing technologies, provides greater accessibility to prosthetic devices, particularly ULP socket manufacturing, in remote and resource-limited settings [9,27]. This enables health care professionals and patients to gain access to prosthetic services even in areas where traditional manufacturing methods may not be readily available, thereby increasing accessibility for

those in underserved and remote areas. Moreover, users can access these services without the need to travel long distances, as 3D printing facilities are increasingly becoming more widespread [1].

Despite the numerous advantages offered by 3D printing in ULP socket design and manufacturing, there are still several limitations and challenges that need to be addressed to further improve the technology and its applications.

3.2. Current Limitations and Challenges

3.2.1. Material Properties and Durability

Despite the advantages, 3D printing faces limitations in terms of material properties and durability [20]. Often, printed prosthetics cannot match the preferred mechanical properties of traditionally fabricated prosthetics. Additionally, not all materials may possess the ideal combination of mechanical and biological properties required for long-term use in prosthetic devices [28]. This limitation can lead to issues such as reduced longevity and the need for more frequent repairs or replacements [10]. Overcoming these challenges demands investigation and development of new materials specifically designed for 3D-printed prosthetics.

3.2.2. Post-Processing and Finishing

3D-printed ULP sockets often require post-processing and finishing techniques, such as smoothing and polishing, to achieve a comfortable and professional finish [24]. While these sockets offer good fit and function, their aesthetics often necessitate additional finishing processes [9]. These steps, including manual post-printing treatments such as surface modifications, can be time consuming and labour intensive, partially offsetting the advantages of rapid prototyping and reduced fitting time [20]. Moreover, the need for such post-processing and finishing can result in added resources and potential complications, presenting an additional challenge associated with 3D printing [9].

3.2.3. Quality Control and Standardization

Ensuring consistent quality control and establishing standardized guidelines for 3D-printed prosthetics, particularly ULP sockets, remain crucial challenges [1,29]. The lack of standardization in 3D printing processes can lead to products with varying levels of quality, which, in turn, may impact their functional efficacy [10]. Developing comprehensive quality control methodologies is necessary to provide health care professionals and patients with confidence in the reliability of 3D-printed ULP sockets. The absence of universal certification and standard testing for 3D-printed sockets further exacerbates the issue [20].

3.2.4. Skill and Training Requirements

The successful adoption and implementation of 3D printing technology in ULP socket design and manufacturing require a well-trained workforce capable of working with the technology [23]. Addressing this challenge necessitates the development of specialized skills, appropriate training programs, and educational resources for clinicians, prosthetists, engineers, and technicians involved in the process [20]. Many professionals in the field of prosthetics require advanced training in additive manufacturing technologies, computer-aided design (CAD) software, and digital technologies to effectively utilize this emerging technology in ULP socket creation [1].

3.2.5. Regulatory and Reimbursement Issues

As 3D printing continues to emerge as a viable method for ULP socket manufacturing, navigating regulatory and reimbursement policies remains a significant challenge (Rengier et al., 2010; Ventola, 2014). Challenges surrounding regulation and reimbursement are prevalent in the world of 3D-printed prosthetics [9]. Existing reimbursement models typically cater to traditionally fabricated prosthetics, and regulatory bodies have yet to develop clear guidelines that encompass the nuances associated with 3D printing [20].

Consequently, there is a need for clear regulatory guidance and reimbursement policies that account for the unique aspects of 3D-printed prosthetic devices. This situation can lead to difficulties in navigating the process for both professionals and end users [10].

3.2.6. Cost Considerations and Material Limitations

Considering the intricacies associated with the customization of Upper Limb Prosthetic (ULP) sockets, it is challenging to achieve economies of scale through traditional manufacturing methods. Despite the perceived advantages of mass production, the cost per unit remains high due to the individualized nature of these devices. However, 3D printing, often touted as a cost-effective solution, also presents challenges. As indicated in the review by Ten Kate, Smit and Breedveld, the affordability of 3D printing is often overstated. The costs associated with 3D printing can escalate when factoring in the limitations of the materials that can be utilized in the process [1].

Material limitations pose a significant challenge for 3D printing. The palette of materials suitable for 3D printing is restricted, which can impede the creation of devices that necessitate special, non-printable materials or components. Although there is a continuous influx of new materials suitable for 3D printing, certain substances, including various fabrics, remain unprintable, thus presenting further obstacles.

Given these constraints, future research should explore a modular design approach. This would entail combining traditional manufacturing methods with more appropriate materials for the standard sections of the prosthetic. Meanwhile, 3D printing could be strategically employed for the parts of the prosthetic that require personalization and frequent replacement. This hybrid approach might provide the best solution, blending the reliability and material versatility of conventional manufacturing with the customization possibilities of 3D printing.

In conclusion, the application of 3D printing technology for ULP socket design and manufacturing has demonstrated promising advantages, including customization, rapid prototyping, cost-effectiveness, diverse material selection, and increased accessibility. However, it is essential to address the current limitations and challenges associated with material properties, post-processing, quality control, skill requirements, and regulatory issues to fully realize its potential in improving the lives of amputees worldwide.

4. Implementation of Mass Customization in ULP Field

4.1. Concept and Implementation of Mass Customization

Mass customization is a contemporary approach in production and marketing that involves catering to customers' diverse needs while maintaining cost-effective strategies. Pioneered in the era of mass production, mass customization shifts the focus from standardized products to personalized services and goods [30,31]. By leveraging digital manufacturing solutions, this concept enables producers to offer a higher degree of product personalization on a large scale [32]. As a result, mass customization has evolved into a significant aspect in modern business, aiming to deliver affordable, customized goods and services that satisfy each customer's requirements [33].

As a contemporary approach in production and marketing, mass customization addresses customers' diverse needs while maintaining cost-effective strategies [34]. In the context of consumer products such as upper limb prosthetic design, this concept ensures the development of personalized, high-performance prostheses [35].

A vital aspect of mass customization in upper limb prosthetics is the use of innovative techniques such as automated design and rapid manufacturing methods. These methodologies allow for the production of low-cost, customized prostheses tailored to individual requirements [34]. Additive manufacturing technologies make it possible to produce prosthetics that cater to diverse needs while reducing costs [36].

In the development of upper limb prostheses, the customization process involves creating prototypes and designs that accommodate patients' specific needs [35]. The resulting prostheses should offer enhanced performance, functionality, and ease of use for

each individual. Research has investigated novel approaches such as personalized liners, adding another level of customization to the prosthesis design [37].

In conclusion, mass customization, as applied to upper limb prosthetic design, emphasizes personalized solutions for individuals with unique requirements, employing innovative manufacturing methods and technologies to develop cost-effective, high-performance prosthetics [34].

4.2. Concept and Implementation of Mass Customization and Its Benefits for Prosthetic Socket Design

Mass customization in upper limb prosthetic design aims to provide personalized, effective, and accessible devices that satisfy individual user preferences and needs while maintaining the cost-efficiency and scalability associated with mass production. The concept revolves around employing modular components, digital design and fabrication, customer involvement, and automated, streamlined processes to create prosthetic devices tailored to specific users, ultimately leading to enhanced fit, comfort, improved functionality, increased user satisfaction, rapid iteration and refinement, and greater accessibility.

Ulrich [38] emphasized the role of product architecture in facilitating the implementation of mass customization through modular components. Modularity provides the flexibility and adaptability manufacturers require to cater to different user requirements by offering a range of interchangeable parts in various sizes, shapes, and functionalities. This approach simplifies the manufacturing process while enabling the production of personalized prosthetic devices that precisely match users' unique needs.

Digital design and fabrication technologies, such as computer-aided design (CAD) and additive manufacturing (3D printing), have revolutionized the prosthetic design and production landscape, as outlined by Huang et al. [39] and Gibson et al. [23]. These technologies allow for accurate, rapid, and cost-efficient manufacturing of customized prosthetic components that conform to a user's specific anatomy, facilitating enhanced fit and comfort.

Customer involvement in the design process is crucial in ensuring products meet user needs, preferences, and expectations. Franke and Piller [40] highlighted the value creation offered by toolkits for user innovation and design, allowing prosthetic users to actively contribute to the design and configuration of their devices. This collaborative approach fosters a better alignment between product design and user expectations, leading to increased satisfaction and higher adoption rates.

Automated and streamlined manufacturing processes, as discussed by Koren and Shpitalni [41], enable greater scalability and efficiency. Advanced manufacturing techniques, process control, and real-time data analytics facilitate rapid response to changing customer requirements, ensuring cost-effective production of personalized prosthetics without compromising quality or accessibility.

4.3. Challenges in Integrating Mass Customization into Prosthetics

Despite the many advantages of mass customization in upper limb prosthetic design, integrating this approach comes with several limitations and challenges. Areas of concern include data collection and management, skills and expertise, standardization and regulations, intellectual property and licensing, quality control and assurance, scalability and infrastructure, as well as user acceptance and education.

Data collection and management, an essential aspect of mass customization, involves gathering accurate and comprehensive user measurements and preferences to create tailored prosthetic devices. As pointed out by Biddiss and Chau [42], accurately collecting this vast and diverse dataset requires robust tools and systems to prevent error and ensure proper data handling.

Skills and expertise in diverse fields, such as advanced manufacturing, prosthetics, and biomedical engineering, are necessary for the successful implementation of mass customization. As noted by Gibson [23], developing and maintaining interdisciplinary

expertise are challenges that must be addressed to ensure a proficient workforce capable of designing and manufacturing customized prostheses.

Standardization and regulations present another significant challenge in the mass customization of prosthetics. As Kyberd and Hill [12] emphasized, coordinating regulatory requirements across various jurisdictions and ensuring compliance with safety and performance standards can be complex, particularly when offering personalized devices catering to unique user needs.

Intellectual property and licensing are crucial aspects in the commercialization of mass-customized prosthetic devices. Birtchnell and Hoyle [43] highlighted the challenges faced by the industry, such as protecting proprietary designs and processes, navigating licensing agreements, and dealing with potential infringement claims.

Quality control and assurance become increasingly critical and complex when dealing with customized products. Salmi [44] stressed the importance of maintaining consistent product quality while catering to the unique requirements of individual users, ensuring optimal performance and user satisfaction in mass-customized prosthetics.

Scalability and infrastructure are essential aspects of mass customization, allowing manufacturers to meet the demand for personalized prosthetic devices without incurring excessive production costs or resource constraints. As discussed by Gebhardt [45], adapting existing production infrastructure and scaling up operations to accommodate mass customization can be a significant challenge, particularly in resource-limited settings.

User acceptance and education are critical factors in the success of mass-customized prosthetic devices. As suggested by Østlie [14], fostering user acceptance and providing appropriate education on device usage and maintenance are essential to maximize the benefits of mass customization in upper limb prostheses.

One of the promising approaches towards enhancing the effectiveness of this integration is the adoption of methods and insights from other fields. A prime example is a case study conducted by Nayak et al. sought to identify the optimal pressure distribution of the prosthetic socket under specific loads using finite element analysis (FEA) and topology optimization with Altair's OptiStruct software [46]. The study incorporated plaster of Paris (PoP) sockets from diverse clinical cases and below-knee (BK) amputees with various stump geometries. The CAD model was created using point cloud data and a meshing approach to generate a volume mesh. This enabled them to quantify the location, intensity, and distribution of stress-strain on the socket, leading to an enhanced socket design. The proposed method integrates FEA with reverse engineering techniques to redesign the socket, thereby improving patient comfort. Moreover, the customized nature of these prosthetic sockets offers the advantage of a lightweight design.

Despite the primary focus of this case study being traditional manufacturing methods, the insights and methodologies it provides could prove to be beneficial when implemented within a mass customization approach using 3D printing. By adjusting the thickness and flexibility of materials, there could be potential improvements in the customization and effectiveness of upper limb prosthetics. Thus, the adoption and adaptation of such interdisciplinary methods could be a significant step forward in addressing the challenges of integrating mass customization into prosthetics.

In conclusion, mass customization of upper limb prosthetics holds great promise for providing personalized, effective, and accessible devices, enhancing the overall well-being and quality of life for users. However, overcoming the associated challenges and limitations is essential to ensure the successful implementation and widespread adoption of mass-customized prosthetic solutions. By focusing on technological advancements, interdisciplinary collaboration, and addressing the specific concerns detailed in this review, the industry can drive innovation and ensure mass-customized upper limb prosthetic devices become a viable and valuable option for improving the lives of users worldwide.

5. Enable Interdisciplinary Collaboration for Upper Limb Prosthetic

The interdisciplinary approach in upper limb prosthetic design has gained increasing attention in recent years due to its potential for enhancing innovation, improving patient outcomes, and ensuring the delivery of high-quality and functional prosthetic devices. This approach involves the integration of various disciplines, such as biomechanics, materials science, engineering, and health care, to create novel and effective solutions for upper limb prosthetic users [2,47]. The importance of interdisciplinary collaboration is paramount for advancing the field of upper limb prosthetic design.

Interdisciplinary collaboration can facilitate the exchange of ideas, knowledge, and expertise among different fields, fostering creativity and innovation in prosthetic design [48]. By working together and combining their respective strengths, professionals from various disciplines can develop more impactful and practical solutions for prosthetic users [49]. This collaboration can lead to the development of prosthetics with improved functionality, comfort, aesthetics, and durability.

Incorporating health care professionals into the design process helps ensure the considerations of users' physical, psychological, and social needs are fulfilled [2]. Additionally, health care professionals can provide valuable insights into the practical limitations and enhancements of various design options [50]. Interdisciplinary collaboration also allows for a more efficient and effective use of resources [51]. By working together and sharing information, professionals from various disciplines can avoid duplication of effort while maximizing the individual contributions of each team member.

One significant challenge in interdisciplinary collaboration is the need for effective communication among professionals from diverse backgrounds [2]. Each discipline often has its language, methods, and assumptions, leading to potential misunderstandings and barriers to collaboration. To overcome this challenge, team members must develop a shared understanding of each other's perspectives and learn to communicate effectively across disciplinary boundaries [49].

Another challenge is the potential for resistance to change, as professionals from various disciplines may be hesitant to embrace innovative ideas or approaches that challenge traditional practices [2]. To address this issue, interdisciplinary teams should foster a culture of openness and be receptive to diverse perspectives, encouraging the exchange of ideas and innovative thinking [48].

Evidence-based management is also crucial to the effective implementation of interdisciplinary collaboration in upper limb prosthetic design [51]. Monitoring and evaluating the team's performance through systematic data collection and analysis can provide valuable insights into areas for improvement and help ensure that the interdisciplinary approach is optimized in relation to patient care and outcomes.

Upon further analysis, it is evident that fostering interdisciplinary collaboration emerges as the catalyst for discovering innovative opportunities in the realm of upper limb prosthetic design. By uniting the prowess of specialists from a myriad of fields to confront intricate challenges, they can synergistically leverage their expertise and discernment, thus facilitating the emergence of cutting-edge advancements in ULP socket design and manufacturing. A meticulous exploration of specific instances pertaining to interdisciplinary research opportunities sheds light on the metamorphic capacity of such an approach, which is well positioned to revolutionize the discipline and significantly enrich the daily experiences of prosthetic users. The ensuing discussion presents a comprehensive examination of these exemplary instances.

5.1. Examples of Opportunities for Interdisciplinary Research in ULP Socket Design and Manufacturing

One area where interdisciplinary research can make a significant impact is the application of 3D printing technology in the development of low-cost, customizable prosthetic devices for children with upper limb differences.

In their study, Zuniga et al. discuss the design of the “Cyborg Beast”, a 3D-printed prosthetic hand that requires wrist function for flexing the fingers and thumb in unison. The low-cost device offers a remote-fitting procedure for people in rural or globally remote areas and the fitting process is efficient and easily scalable, making it suitable for children’s rapid growth [19]. Future interdisciplinary research could explore prosthetic functionality improvements, durability, benefits, and rejection rates. Ten Kate, Smit and Breedveld’s review highlights the benefits of 3D printing, such as customizability, rapid production, and reduced costs [1]. Exploring new materials and fabrication methods can improve the robustness, durability, and aesthetics of 3D-printed ULP sockets, which can be an area of focus for interdisciplinary research involving biomedical engineers, materials scientists, and rehabilitation professionals.

Advancements in 3D printing, such as Sengeh and Herr’s variable-impedance prosthetic socket designed from magnetic resonance imaging data, can benefit the development of more comfortable and effective prosthetic sockets for transtibial amputees [52]. In this study, the variable-impedance socket reduced contact pressure on bony prominences and increased the self-selected walking speed of the participant, showcasing the potential for improved prosthetic devices. Additional interdisciplinary research on this method can assess the long-term effects on socket pressure distribution and socket variable impedance properties.

Furthermore, Lunsford et al.’s literature review of innovations in 3D printing within physical medicine and rehabilitation emphasized the importance of identifying suitable materials and processes for 3D-printed prosthetic devices [26]. Paterson et al.’s research compared different 3D printing methodologies for producing upper limb orthoses, finding that selective laser sintering (SLS), stereolithography (SLA), and PolyJet material jetting are currently viable for clinical use [24]. Interdisciplinary collaboration can also lead to innovative design modifications, such as those demonstrated by Laszczak et al. on the introduction of low-cost 3D-printed prosthetic pressure sensors [53]. Those research highlight the importance of interdisciplinary collaboration between biomedical engineers, materials scientists, and rehabilitation professionals can lead to the discovery of innovative design improvements to ULP socket development.

Incorporating advanced technologies such as artificial intelligence (AI) and virtual reality (VR) into this field offers further research opportunities. Murray et al.’s [7] study suggests that immersive VR can reduce phantom limb pain, opening doors for research on the integration of VR and AI in the design process and patient rehabilitation.

In addition to the technological advancements in 3D printing, interdisciplinary research can also explore the integration of artificial intelligence (AI) in robotic prostheses. The study by Laschowski, Razavian and McPhee [54] highlighted how researchers developed AI-powered robotic legs using wearable cameras. While this specific study focuses on lower-limb prostheses, these technological innovations can inspire the development of advanced, AI-powered ULP devices as well.

Apart from the technological aspect, studies on patient satisfaction and prosthetic device usage provide valuable insights for the development of improved ULP sockets. The research by McFarland et al. [55] explored the use of prosthetic devices in veterans and service members with upper limb loss, while Biddiss and Chau surveyed prosthetic device use and abandonment over the last 25 years [42]. Information from these studies can offer important perspectives for refining the functional and aesthetic aspects of prosthetic devices.

Understanding the prevalence of limb loss and the potential applications of emerging technologies can also inform interdisciplinary research efforts. Ziegler-Graham et al.’s study on estimating the prevalence of limb loss in the United States from 2005 to 2050 highlights the growing need for innovative solutions in prosthetic device development [56]. It is essential to understand the user satisfaction for long-term ULP prosthesis use, as highlighted by McFarland et al. [55]. Only then, and combining knowledge from biomechanics, materials

science, and psychology can lead to a better understanding of user needs, which in turn may improve retention and satisfaction rates among ULP prosthesis users.

McFarland et al.'s study also highlights the importance of user satisfaction in long-term ULP prosthesis use. Combining knowledge from biomechanics, materials science, and psychology can lead to a better understanding of user needs, which in turn may improve retention and satisfaction rates among ULP prosthesis users [55].

Mass customization, demonstrated by Pallari, Dalgarno and Woodburn et al.'s work on foot orthoses [57], shows the potential of 3D printing in creating personalized prosthetics catered to individual needs. Developing customizable ULP sockets with tailored mechanical properties could significantly improve both fit and functionality for users.

Lastly, Biddiss and Chau's [42] research emphasizes the importance of understanding factors leading to ULP prosthesis abandonment. Interdisciplinary research combining insights from biomedical engineering, psychology, and social sciences can help identify barriers to continued use and devise strategies to increase long-term adoption and satisfaction rates.

The aforementioned examples serve to illustrate the considerable potential of interdisciplinary research in the design, fabrication, fitting, and maintenance of ULP, paving the way for the development of increasingly personalized, comfortable, and efficient prosthetic devices. Collaborative efforts encompassing a range of disciplines, such as biomechanics, materials science, psychology, artificial intelligence, and virtual reality, have the capacity to yield remarkable advancements in ULP design, ultimately enhancing the quality of life for individuals with limb loss.

Nevertheless, interdisciplinary research is not without its challenges, particularly with regard to effective communication and collaboration among researchers originating from disparate disciplinary backgrounds [3]. Each discipline possesses its own lexicon, concepts, and methodologies, which may impede efficacious communication and cooperation. Jeffrey [3] and Bruce et al. [8] posit that forging common ground and fostering mutual understanding among team members are essential for the success of interdisciplinary research. This might necessitate additional time and effort during the project's initial stages to establish effective communication channels and engender trust among researchers from various backgrounds. This study endeavours to explain the opportunities and challenges inherent in interdisciplinary research through an analysis of diverse cross-disciplinary studies.

5.2. Challenges and Opportunities for Interdisciplinary Research

Interdisciplinary research has become increasingly important in recent years, offering significant opportunities for innovation by harnessing the knowledge and expertise of professionals from diverse fields [4,5]. Upper limb prosthetic socket design and manufacturing are areas where interdisciplinary research can play a crucial role, as they involve the integration of various fields such as engineering, materials science, biomechanics, and health care. By engaging in interdisciplinary research, researchers can develop innovative solutions that address the diverse needs of prosthetic users.

However, interdisciplinary research also presents several challenges, such as the need for effective communication and collaboration among researchers with different disciplinary backgrounds [3]. Each discipline has its language, concepts, and methodologies, which may hinder effective communication and collaboration. Both Jeffrey [3] and Bruce et al. [8] suggest that establishing common ground and shared understanding among team members are crucial for successful interdisciplinary research. It might require additional time and effort in the initial stages of the project to develop effective communication channels and foster trust among researchers from different backgrounds.

Feller, Ailes and Roessner [58] highlight the valuable contributions and potential impacts that research universities can make on technological innovation within various industries, including upper limb prosthetic design and manufacturing, through interdisciplinary collaborations in Engineering Research Centers (ERCs). Bozeman and Boardman [59] discuss the challenges that managing multipurpose and multidisciplinary university re-

search centres entail, as institutional innovation is often required in order to accommodate collaborative work among researchers from diverse fields.

One opportunity in interdisciplinary research in upper limb prosthetic socket design is the potential for innovation in the field. By incorporating ideas and approaches from different disciplines, researchers can develop novel solutions to address the multifaceted problems associated with prosthetic socket design [58,59]. For example, the integration of advanced materials and engineering techniques can lead to the development of lightweight, comfortable, and durable prosthetic sockets that can withstand the stresses induced by the body's movements.

Furthermore, interdisciplinary research enables researchers to address the various user needs more effectively. Upper limb prosthetic users have unique needs and preferences, including comfort, aesthetics, functionality, and durability [6]. By engaging with health care professionals, researchers can better understand the users' needs and develop tailored solutions to meet those needs [60].

However, challenges in interdisciplinary research include the potential resistance to new ideas and approaches from traditional disciplinary frameworks [61]. Researchers may hold different epistemological and ontological beliefs, which can cause disagreements and hinder collaborative work [5]. To address this issue, researchers need to be open to diverse perspectives and engage in constructive dialogue that fosters integration and innovation [60].

Moreover, the evaluation of interdisciplinary research presents significant challenges. As Klein et al. [4] point out, interdisciplinary research often has variable goals and requires unique criteria and indicators to measure success. The current academic reward system may not fully recognize the contributions of interdisciplinary research, which can limit funding opportunities and career recognition [5,59]. Addressing these challenges and providing support for interdisciplinary researchers are essential for fostering innovation in the field.

In conclusion, interdisciplinary research in upper limb prosthetic socket design and manufacturing offers significant opportunities for the development of innovative solutions that address the multifaceted issues associated with prosthetic use. By embracing the unique perspectives and integrating diverse disciplines, researchers can design practical and effective prosthetic devices that meet users' varied needs. However, overcoming the communication, collaboration, resistance to change, and evaluation challenges associated with interdisciplinary research is crucial for successful implementation. With proper support and openness to diverse perspectives, interdisciplinary research can indeed pave the way for ground-breaking advances in upper limb prosthetic socket design and manufacturing.

However, to achieve this, researchers must engage in continuous dialogue to develop a shared understanding and respect for different disciplinary perspectives and approaches, integrate diverse methodologies and epistemologies, and promote institutional innovation that accommodates collaborative research efforts. Furthermore, the encouraging women enter into this science field, as suggested by Rhoten and Pfirman [5], and the consideration of contextual influences on transdisciplinary collaboration, as discussed by Stokols et al. [6], can enhance interdisciplinary research's effectiveness and productivity in upper limb prosthetic socket design and manufacturing. By addressing these challenges and capitalizing on the opportunities provided by interdisciplinary research, significant improvements can be made in the lives of individuals requiring upper limb prosthetic devices.

6. Conclusions

Interdisciplinary research offers significant opportunities and challenges in the field of upper limb prosthetic socket design and manufacturing. Embracing interdisciplinary collaboration has the potential to drive innovation by integrating different disciplines, such as engineering, materials science, biomechanics, health care, artificial intelligence, and virtual reality. By addressing the diverse needs and preferences of prosthetic users and

focusing on technology advancements, researchers and professionals can greatly enhance the quality of life for individuals requiring upper limb prosthetic devices [1,2].

However, interdisciplinary research also presents important challenges, mainly concerning effective communication and collaboration among researchers from different disciplinary backgrounds [3]. To overcome these challenges, researchers need to engage in continuous dialogue, develop shared understanding and respect for different disciplinary perspectives and approaches, and integrate diverse methodologies and epistemologies [8]. Promoting institutional innovation that accommodates collaborative research efforts is critical for the success of interdisciplinary research in upper limb prosthetic socket design and manufacturing [6,59].

Encouraging women to enter this field, as suggested by Rhoten and Pfirman [5], and considering contextual influences on transdisciplinary collaboration, as discussed by Stokols et al. [6], are essential steps that can enhance the effectiveness and productivity of interdisciplinary research in prosthetic socket design and manufacturing. This approach not only contributes to building a more inclusive and diverse pool of experts, but also fosters creativity and innovation in a field where user satisfaction is paramount [14,55].

Moreover, addressing the limitations and challenges associated with 3D printing, such as material properties, durability, quality control, and training requirements, is essential for the technology to reach its full potential in the development of upper limb prosthetic socket design and manufacturing [20,26]. Furthermore, the integration of emerging technologies such as AI and VR opens new research opportunities that can transform prosthetic device development and improve outcomes for users [7,54].

The potential of interdisciplinary research in upper limb prosthetic socket design and manufacturing can be realized when researchers, professionals, and institutions work together to embrace interdisciplinary collaboration, address the challenges it presents, and capitalize on the opportunities offered by this approach. By doing so, significant improvements can be made in the lives of individuals requiring upper limb prosthetic devices, ultimately contributing to their well-being and quality of life.

Through the examination of case studies, discussions around the advantages and drawbacks associated with interdisciplinary research, and consideration of user satisfaction and prosthetic usage, this paper provides an invaluable insight and direction for researchers and professionals seeking to contribute to this transformative field. In summary, addressing challenges and seizing opportunities provided by interdisciplinary research will be instrumental in fostering meaningful advancements in the lives of those who rely on upper limb prosthetic devices.

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