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Integration of Reverse Engineering and Additive Manufacturing Methods in the Design and Development of Prosthetic Products : A Literature Review

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ABSTRACT

The integration of reverse engineering (RE) and additive manufacturing (AM) in the design and development of prosthetic devices has shown significant potential for improving the customization, efficiency, and overall quality of these essential medical aids. This paper reviews recent advancements in the use of RE and AM for prosthetics, highlighting key methodologies and findings from various studies. The results demonstrate that combining these technologies can enhance mechanical properties, dimensional accuracy, and user satisfaction while reducing production costs and time. However, challenges such as material biocompatibility and the need for standardized frameworks remain. Continued research and collaboration among researchers, clinicians, and industry stakeholders are essential to fully realize the potential of RE and AM in prosthetic development, ultimately improving the quality of life for individuals with limb loss.
Keyword: Additive Manufacturing, Customization, Prosthetics, Reverse Engineering, Biocompatibility

ABSTRAK

Integrasi *reverse engineering* (RE) dan *additive manufacturing* (AM) dalam desain dan pengembangan perangkat prostetik telah menunjukkan potensi yang signifikan untuk meningkatkan kustomisasi, efisiensi, dan kualitas keseluruhan dari alat bantu medis. Penelitian ini mengulas kemajuan terkini dalam penggunaan RE dan AM untuk prostetik, menyoroti metodologi dan temuan utama dari berbagai penelitian. Hasilnya menunjukkan bahwa menggabungkan teknologi ini dapat meningkatkan sifat mekanis, akurasi dimensi, dan kepuasan pengguna sekaligus mengurangi biaya dan waktu produksi. Namun, tantangan seperti material *biocompability* dan kebutuhan akan kerangka kerja standar tetap ada. Penelitian dan kolaborasi berkelanjutan antara peneliti, dokter, dan pemangku kepentingan industri sangat penting untuk sepenuhnya mewujudkan potensi RE dan AM dalam pengembangan prostetik, yang pada akhirnya meningkatkan kualitas hidup individu dengan kehilangan anggota tubuh.
Keyword: Additive Manufacturing, Kustomisasi, Prostetik, Reverse Enginering, Biocompability

1. Introduction

According to the World Health Organization (WHO), approximately 10% of the global population, which is about 650 million people, live with disabilities [1]. A significant majority, around 80%, reside in low-income countries [2]. Disabilities can manifest as functional impairments that can be objectively measured, such as the loss or abnormality of body parts, like limb amputations or paralysis in certain body parts [3]. These conditions can have varied impacts on individuals, for instance, brain damage can lead to intellectual disabilities, hyperactivity, or blindness [4]. A significant issue related to disabilities is the increasing number of children experiencing amputations due to traumatic accidents or congenital disabilities. The need for prosthetics for children is particularly complex due to their small size, constant growth, and psychosocial development [5].

The development of electrically powered (myoelectric) and body-powered (mechanical) prosthetic devices aims to meet the needs of children. However, the costs of maintenance and replacement often pose challenges for many families, especially when private insurance and government funding are insufficient [6]. The complexity and high costs of these prosthetic devices limit access, particularly for children from low-income families or developing countries [7]. In Indonesia, the National Health Insurance Program (JKN) aims to ensure access to basic health services for all citizens. Nevertheless, the development of orthotic and prosthetic services remains slow, while the demand for these devices continues to rise due to the high number of people with disabilities [8].

Prosthetics play a crucial role in improving the quality of life for individuals who have lost limbs. Advanced technologies such as reverse engineering (RE) and additive manufacturing (AM) have opened new opportunities in the design and development of more personalized and efficient prosthetics [9]. RE allows for the accurate collection of anatomical data from patients, which can then be used to create digital models of the missing limbs [10]. Conversely, AM enables the production of prosthetic components based on these digital models with high precision and biocompatible materials [11].

Integrating RE and AM in prosthetic development offers various benefits, including creating devices that better meet the individual needs of patients [12]. This process allows for the development of prosthetics that not only replicate the shape and function of the original limbs but can also be tailored to the unique characteristics of the patients, such as weight and body shape [13]. A study indicates that using AM in prosthetic development can reduce costs and delivery times, as well as enhance the comfort and functionality of these devices [14].

Reverse engineering often struggles with inaccuracies in data capture, especially for complex geometries, and may result in incomplete or flawed 3D models due to limitations in scanning resolution or access. Meanwhile, AM, though offering great flexibility in producing complex parts, faces challenges such as material limitations, slower production speeds, and surface finish quality issues. Integrating reverse engineering with additive manufacturing enables the precise design of parts based on real-world measurements, improving the accuracy of prototypes and customized products [15].

However, the application of these technologies also faces several challenges [16]. One major challenge is the lack of a systematic framework that integrates RE technology with AM procedures in prosthetic manufacturing [17]. Research shows that there is still a gap between expectations and reality in the application of AM in prosthetic and orthotic clinics, particularly regarding optimal design and biomechanical evaluation of the produced devices [18].

Moreover, the importance of personalization in prosthetic manufacturing cannot be overlooked [2]. By using anatomical data collected through RE technology, AM can produce prosthetics that are fully customized to the specific needs of patients [8]. This not only enhances comfort but also the clinical effectiveness of the devices [19]. Recent research shows that prosthetics produced with this approach exhibit adequate biomechanical performance and can significantly improve the quality of life for patients [20].

The development of prosthetics using AM technology also allows for significant reductions in production time and costs [3]. The AM process enables the quick and efficient production of prosthetic components, reducing patient wait times and overall production costs [10]. For instance, a study shows that prosthetics made with AM technology can reduce production time by up to 95% and costs by up to 55% compared to traditional methods [21].

Overall, the integration of reverse engineering and additive manufacturing methods in the design and development of prosthetics offers numerous potential benefits, including better personalization, time and cost efficiency, and improved clinical outcomes [4]. Nevertheless, the challenges in applying these technologies require further research and the development of a more comprehensive framework to ensure that their benefits can be fully optimized [9].

2. Literature Review

The integration of reverse engineering (RE) and additive manufacturing (AM) in prosthetic design has shown significant potential in creating highly personalized and efficient prosthetic devices. RE enables the precise capture of anatomical data, which can be transformed into digital models, forming the basis for AM [18]. Stenvall et al. in 2020 explored the use of forest-based composites in transtibial prostheses, demonstrating that the integration of bio composites with AM techniques enhanced mechanical strength and user satisfaction. This approach underscores the versatility of AM in customizing prosthetics to meet specific patient needs [21].

One of the primary benefits of using AM in prosthetic development is the ability to achieve high dimensional accuracy and detailed reproduction of anatomical features [7]. Unkovskiy et al. in 2019 conducted a comparative analysis of various AM methods for creating auricular prosthesis replicas. Their findings indicated that fused deposition modelling (FDM) provided superior dimensional accuracy and skin texture reproduction compared to other techniques like selective laser sintering (SLS) and stereolithography (SL). This precision is crucial for ensuring the functional and aesthetic quality of prosthetic devices [19].

In the realm of eye prosthetics, Sedlak et al. in 2020 demonstrated the application of RE and AM in producing customized eye prostheses. By utilizing 3D scanning and digital modelling, they were able to create detailed and patient-specific prosthetic eyes. The study highlighted the effectiveness of combining these technologies to overcome the limitations of traditional manual methods, resulting in improved fitting and patient satisfaction [3].

The use of AM in the production of upper limb prosthetics has also been extensively researched. Manero et al. in 2023 discussed evolving 3D-printing strategies for structural and cosmetic components in upper limb prostheses. They found that integrating multiple manufacturing techniques, including AM and thermoforming, resulted in significant weight reduction and improved device performance. This approach not only enhances the functionality of the prosthetics but also addresses common issues such as device weight and user comfort [20].

Miechowicz et al. in 2021 detailed a method for designing and manufacturing craniofacial prostheses using AM. Their study utilized photogrammetry, CAD-based sculpting, and AM to create patient-specific prosthetic devices. The workflow demonstrated significant benefits, including reduced production costs and the ability to tailor prosthetics to the unique anatomical features of patients. Despite some challenges in material selection and aesthetic outcomes, the study showcased the potential of AM in producing highly customized and functional prosthetic solutions [5].

In conclusion, the integration of RE and AM in prosthetic design offers substantial benefits, including high customization, improved dimensional accuracy, and enhanced user satisfaction [13]. These technologies enable the creation of prosthetic devices that are tailored to the individual needs of patients, providing better fit, comfort, and functionality [20]. While there are challenges to be addressed, ongoing research and advancements in AM technologies continue to enhance the capabilities and applications of these innovative methods in prosthetic development [22].

3. Result and Discussion

Table 1. Literature Review of RE and AM in Prosthetics

No	Authors & Year	Title	Methodology	Key Findings	Conclusion
1	Stenvall et al., 2020 [21]	Additive Manufacturing of Prostheses Using Forest-Based Composites	Developed transtibial prostheses using bio composites (PP and MFC) via FDM	Enhanced mechanical strength and successful clinical trials showing high user satisfaction	Combining bio composites and AM produces effective and sustainable prosthetics
2	Unkovskiy et al., 2019 [19]	Comparative Analysis of Dimensional Accuracy and Skin Texture	Compared FDM, SLS, and SL for auricular prostheses replicas	FDM provided superior dimensional accuracy and best skin surface reproduction	FDM is most effective for producing detailed and accurate prosthetic replicas

No	Authors & Year	Title	Methodology	Key Findings	Conclusion
		Reproduction of Auricular Prostheses Replicas			
3	Sedlak et al., 2020 [3]	Design and Production of Eye Prosthesis Using 3D Printing	Used 3D scanning, CAD, and PolyJet AM for eye prostheses	Achieved high-quality aesthetic results, with challenges in material biocompatibility	RE and AM can produce highly customized prostheses, material selection is crucial
4	Barbin et al., 2020 [8]	3D Metal Printing in Dentistry: An In Vitro Biomechanical Comparative Study	Investigated SLM and EBM for full-arch implant-supported prostheses	Both methods provided acceptable biomechanical properties; spark erosion improved marginal fit	AM technologies are feasible for complex prosthetic frameworks
5	Miechowicz et al., 2021 [5]	Method of Designing and Manufacturing Craniofacial Soft Tissue Prostheses Using AM	Utilized photogrammetry, CAD, SLA, and Vacuum Casting	Produced functional prototypes but highlighted the need for improved biocompatible materials	New technologies can reduce production costs and time, enhancing patient-specific prosthetics
6	Nicoloso et al., 2021 [6]	Towards 3D printing of a monocoque transtibial prosthesis using a bio-inspired design workflow	Used 3D imaging, modelling, optimization, and AM for transtibial prosthesis	Successful fabrication of functional prosthesis, significant reduction in cost, weight, and production time	Workflow provides cost-effective and functional prosthetics with improved accessibility
7	Żukowska et al., 2021 [14]	Study on Properties of Automatically Designed 3D-Printed Customized Prosthetic Sockets	Compared sockets made of rigid PLA and elastic TPE, designed automatically based on 3D-scanned limb	Most products fulfilled strength criteria, with varying fitting and comfort	Recommendations for materials and process parameters for automated design and production

The integration of reverse engineering (RE) and additive manufacturing (AM) in prosthetic development presents a multifaceted approach to enhancing prosthetic technology. The studies reviewed in Table 1 provide a comprehensive overview of various methodologies and their outcomes, aligning well with the research objective of understanding the synthesis and application of these technologies in prosthetics.

The first study demonstrates the potential of using bio composites in transtibial prostheses. The combination of polypropylene (PP) and micro fibrillated cellulose (MFC) significantly improved mechanical properties, highlighting the sustainability and effectiveness of integrating bio composites with AM. This approach aligns with the research objective by showcasing how RE and AM can produce high-performance, environmentally friendly prosthetics tailored to individual needs.

In the second study, the focus on dimensional accuracy and skin texture reproduction for auricular prostheses underscores the precision capabilities of AM technologies. The superior performance of fused deposition modeling (FDM) in achieving high accuracy and detailed reproduction of anatomical features emphasizes the importance of selecting appropriate AM techniques. This precision is critical for ensuring the functional and aesthetic quality of prosthetic devices, directly addressing the research aim of enhancing prosthetic development through advanced manufacturing methods.

The third study explores the customization of eye prostheses using 3D scanning and PolyJet technology. The high-quality aesthetic results achieved, despite challenges with material biocompatibility, highlight the potential for highly personalized prosthetic solutions. This study supports the research objective by demonstrating how RE and AM can produce customized prosthetics that meet specific patient needs, although it also underscores the ongoing need for advancements in biocompatible materials.

In the fourth study, the investigation into full-arch implant-supported prostheses produced using selective laser melting (SLM) and electron beam melting (EBM) demonstrates the feasibility of using AM for complex prosthetic frameworks. The study's findings that both methods provided acceptable biomechanical properties and that spark erosion improved marginal fit illustrate the practical applications of these technologies in clinical settings. This directly supports the research objective by showcasing the reliability and effectiveness of AM in producing prosthetics that meet clinical standards.

The final study details the method for designing and manufacturing craniofacial prostheses using photogrammetry, CAD, stereolithography (SLA), and vacuum casting. The significant reduction in production costs and time achieved in this study aligns with the research goal of improving efficiency in prosthetic manufacturing. However, the need for improved biocompatible materials highlighted in this study points to an area requiring further research and development, ensuring that the benefits of RE and AM are fully realized.

In summary, these studies collectively demonstrate the significant advancements and challenges in integrating RE and AM for prosthetic development. The research aligns with the objective of improving prosthetic technology through personalized, efficient, and high-quality manufacturing methods. These findings underscore the potential of RE and AM to revolutionize prosthetic development, although continued research and material advancements are necessary to optimize these technologies fully.

4. Conclusion

The integration of reverse engineering (RE) and additive manufacturing (AM) in prosthetic development has demonstrated substantial benefits, including enhanced customization, improved mechanical properties, and increased production efficiency. The reviewed studies illustrate the effectiveness of these technologies in creating high-quality, patient-specific prosthetic devices. However, challenges such as the need for better biocompatible materials and the development of systematic frameworks for integrating RE and AM remain. Overall, the findings suggest that RE and AM hold significant potential to revolutionize prosthetic development, offering tailored solutions that enhance the quality of life for individuals with limb loss.

To fully realize the potential of RE and AM in prosthetics, future research should focus on addressing the material challenges by developing and testing new biocompatible materials that can enhance the comfort and safety of prosthetic devices. Additionally, creating standardized frameworks and protocols for the integration of RE and AM processes will be crucial in ensuring consistent quality and performance in prosthetic manufacturing. Collaboration between researchers, clinicians, and industry stakeholders will be essential in advancing these technologies and translating them into practical, widely accessible solutions for patients worldwide.

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