© Aluna Publishing WL Wiadomości Lekarskie Medical Advances, VOLUME LXXVIII, ISSUE 3, MARCH 2025

REVIEW ARTICLE

CONTENTS

Advances in 3D printed orthotics for rehabilitation

Aleksandra Bełżek[1], Marta Żerebiec[2], Natalia Saj[1], Zuzanna Rupeć[1], Paweł Kamiński[2], Mateusz Kaczmarski[1], Karolina Turżańska[3]

[1]STUDENT SCIENTIFIC CLUB OF THE LABORATORY FOR MUSCULOSKELETAL SYSTEM RESEARCH, MEDICAL UNIVERSITY OF LUBLIN, LUBLIN, POLAND

[2]STUDENT SCIENTIFIC ASSOCIATION AT THE DEPARTMENT OF REHABILITATION AND ORTHOPEDICS, MEDICAL UNIVERSITY OF LUBLIN, LUBLIN, POLAND

[3]DEPARTMENT OF REHABILITATION AND ORTHOPEDICS, MEDICAL UNIVERSITY OF LUBLIN, LUBLIN, POLAND

ABSTRACT

3D printing technology has revolutionized medicine, particularly in orthopedic oncology and rehabilitation, by enabling the creation of customized implants, prostheses, and surgical tools. Its ability to produce complex, patient-specific structures with precise mechanical properties has significantly improved surgical outcomes and treatment effectiveness. Additionally, advancements in digital imaging and computer-aided design/computer-aided manufacturing (CAD/CAM) technologies have streamlined the design and manufacturing process, reducing production time while enhancing comfort and functionality. The continuous development of materials and printing techniques ensures further innovations in personalized medical solutions, making 3D printing a key tool in modern healthcare.The aim of this review is to evaluate the usefulness and development of 3D printing in rehabilitation, focusing on its impact on prosthetics and orthotics. The review of contemporary literature confirms that 3D printing significantly enhances the customization, efficiency, and accessibility of prosthetics and orthotics in rehabilitation. Studies indicate that 3D-printed devices provide comparable or superior biomechanical performance and comfort compared to traditionally manufactured solutions. Additionally, advancements in digital imaging and CAD/CAM technologies have optimized the design and production process, reducing manufacturing time while maintaining precision. 3D printing has emerged as a groundbreaking technology in rehabilitation, offering highly customizable and cost-effective solutions for prosthetics and orthotics. The integration of digital imaging and CAD/CAM technologies further refines the design process, ensuring greater precision. As research and material advancements continue, 3D printing is expected to play an increasingly significant role in rehabilitation, improving patient care and quality of life.

KEY WORDS: 3D printing, orthoses, rehabilitation.

Wiad Lek. 2025;78(3):539-543. doi: 10.36740/WLek/202602 DOI

INTRODUCTION

3D printing technology is gaining significance in medicine, particularly in orthopedic oncology. Three-dimensional models of bones, defects, and tumors are used for precise surgical planning, the design of custom surgical tools, and the production of implants tailored to patient needs. This technology began developing in the 1990s, and its growing popularity stems from the ability to precisely control the entire process, create non-standard shapes, and obtain structures with specific mechanical properties. With lower costs, reduced production time, and layer-by-layer modeling, it is possible to accurately replicate structures at both the micro- and macroscopic levels.3D printing technology has revolutionized medicine by enabling the creation of implants, prostheses, and surgical tools tailored to individual patient needs. The most significant applications of this method include personalized prostheses, surgical preparation and training, simulation models, and tissue engineering [1, 2]. 3D printing allows for extensive prosthetic customization, enabling the adjustment of shape, size, color, and socket design without interfering with the production process. Upper limb loss may result from congenital defects or amputation. A hand prosthesis helps restore some of the lost limb's functions, making daily activities easier. One method of manufacturing such prostheses is 3D printing, which allows precise adaptation to the anatomical needs of the user [3]. Individually fitted joint prostheses play a key role in treating complex musculoskeletal disorders, especially when standard components fail to provide an adequate fit in terms of shape and size. These prostheses can enhance both clinical functionality and joint biomechanics compared to standard solutions while also minimizing the risk of nerve damage during surgery [4].It ensures high efficiency and cost-effectiveness [5-7]. It also serves as an affordable alternative for patients in developing countries and those with limited access to medical care [8]. As a result, 3D printing has become a leading manufacturing technique in medicine and healthcare, with applications in fields such as dentistry, tissue engineering and regenerative medicine, tissue models, medical devices, anatomical models, and drug formulation [5-7].

AIM

This review aimed at briefly presenting up-dated information on advances in 3D printed prosthetics and orthotics for rehabilitation focusing on its diversity and need for complex approach.

MATERIALS AND METHODS

The research material was a review of the current literature advances in 3D printed prosthetics and orthotics for rehabilitation. For this purpose, the available database was searched using the Pub Med website, Google Scholar.

REVIEW

ORTHOSES AND 3D PRINTING

Orthoses are devices placed on the body or limbs to modify both the functional and structural aspects of the neuromuscular and skeletal systems. They serve as support for parts of the body where function and mechanics have been disrupted [9, 10]. These devices offer a range of functions including control, guidance, limitation, or immobilization of body parts, thereby aiding in weight distribution and facilitating the rehabilitation process of injured limbs [9]. Deaver outlined the primary objectives of braces approximately 50 years ago, which include preventing and correcting deformities, providing support for body weight, and managing involuntary movements. While these are recognized as essential functions, in the rehabilitation field, braces primarily focus on enhancing residual function [10].

In the review conducted by Choo YJ, Boudier-Revéret M, and Chang MC, it was discovered that 3D printed orthoses exhibit notable enhancements in biomechanical and kinematic parameters, comparable to conventional orthoses. Moreover, individuals participating in the studies expressed notable comfort while wearing 3D printed orthoses. Furthermore, in several instances, the effectiveness and comfort associated with 3D printed orthoses surpassed those of conventional counterparts [11]. This indicates a significant advantage of 3D printed orthoses, particularly in terms of comfort and performance.

The combination of comparable comfort results and the quicker, more consistent manufacturing process of 3D-printed orthoses presents a compelling benefit, especially for patients prone to conditions such as diabetic foot ulcers [12]. Research on customized 3D printed ankle-foot orthoses (AFO) has demonstrated their efficacy in reducing damage related to plantar lesions and enhancing comfort in individuals with plantar fasciitis compared to prefabricated traditional AFOs [13]. Additionally, studies have indicated that 3D-printed foot orthoses (FOs) are more effective in addressing issues like arch height drop compared to conventionally-made FOs. Analytical assessments have shown that both types of FOs decrease ankle plantarflexion moment and power in comparison to not using FOs at all. Overall, these findings lend support to the use of 3D-printed FOs, highlighting their comparable effectiveness to traditional FOs, particularly for individuals with flat feet experiencing unilateral heel pain [14].

PRODUCTION/DESIGNING

Recent advancements in technology have paved the way for the development of alternative methods for manual casting and rectification. These advancements encompass the utilization of computer-aided design/ computer-aided manufacturing (CAD/CAM) and 3D imaging techniques to create a virtual representation of the patient's anatomy. Among these techniques, three-dimensional imaging methods like 3D scanning offer promising avenues for digital design and biomedical modeling through reverse engineering approaches [15,16]. These methodologies facilitate digital rectification, positive mold production, and brace design, thereby significantly reducing the time required to fabricate braces by up to 50% [15]. One notable advantage of these design processes lies in the ability to craft insoles based on foot scans, eliminating the need for individual molds for each consumer [17]. Rapid prototyping technologies (RPT) which are using 3D print, have witnessed substantial growth in the biomedical domain, offering novel avenues for morphological acquisition and device fabrication [18]. The integration of RPT with complementary technologies, such as casting or soft material injection within rapid molds, allows for the creation of final devices with gradient stiffness profiles, enhancing comfort and ergonomics [15,19]. These synergistic approaches hold immense potential for revolutionizing the rehabilitation process by enhancing device accuracy and functionality.

MATERIALS

The materials commonly utilized for the production of 3D printed orthoses encompass a variety of options, including polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), thermoplastic polyurethane (TPU), and polycaprolactone (PCL) [3,13]. Each of these materials brings unique properties to the table, catering to different needs and preferences in orthotic design and functionality. Polylactic acid (PLA), for instance, stands out as an environmentally friendly option [11]. It boasts attributes such as the absence of environmental hormones or heavy metals, making it a sustainable choice. Moreover, PLA showcases excellent renewability and biocompatibility, aligning well with the growing emphasis on eco-conscious materials in orthotic manufacturing [11, 20]. Acrylonitrile butadiene styrene (ABS) presents another noteworthy option, characterized by its remarkable impact resistance and ease of processability. Comprising three components—acrylonitrile, butadiene, and styrene, this material offers a balance of strength and flexibility, making it suitable for various orthotic applications [11, 21, 22]. Thermoplastic polyurethane (TPU) emerges as a frontrunner in terms of mechanical properties. With attributes such as high tensile strength, tearing strength, and abrasion resistance among thermoplastic elastomers, TPU proves to be an ideal choice for orthoses requiring durability and resilience [11].

Looking ahead, the trajectory of development in this field is poised to focus on innovation in both structural design and material composition. By continually refining orthotic structures and materials, there is potential to enhance comfort levels, thereby ensuring the success and widespread adoption of new orthoprosthetic aids [18].

DISCUSSION

The application of 3D printing in orthotics has demonstrated significant advancements in customization, efficiency, and patient outcomes. Compared to conventional orthotic manufacturing, 3D-printed devices provide improved adaptability to individual anatomical structures, reducing discomfort and enhancing therapeutic effectiveness [2-6]. The ability to create patient-specific orthoses through computer-aided design (CAD) and rapid prototyping technologies allows for precise structural modifications that accommodate biomechanical needs. One of the key advantages of 3D printing in orthotics is the reduced production time [15, 16]. Traditional methods often require extensive manual labor and multiple fittings, whereas 3D printing enables faster fabrication while maintaining accuracy [15]. This is particularly beneficial for patients requiring immediate orthotic solutions, such as those recovering from injuries or managing progressive musculoskeletal disorders [12]. Additionally, digital modeling reduces material waste and lowers costs, making orthotic solutions more accessible, especially in low-resource settings [11]. Material selection plays a crucial role in the effectiveness and durability of 3D-printed orthoses. Studies have highlighted the use of PLA, ABS, and TPU, each offering distinct mechanical properties suited to different orthotic applications. PLA is recognized for its biocompatibility and sustainability, while ABS provides high impact resistance, and TPU offers flexibility and resilience. The choice of materials significantly impacts the overall performance, comfort, and longevity of the devices [11, 18,20-22]. Despite the numerous advantages, challenges remain in the widespread adoption of 3D-printed orthoses. Ensuring consistent quality, optimizing material properties for long-term use, and improving regulatory frameworks are necessary to fully integrate this technology into clinical practice [11]. Additionally, while 3D printing enhances customization, achieving the same level of durability as traditionally manufactured orthoses requires further research into composite materials and hybrid manufacturing approaches. Future advancements in 3D printing, including multi-material printing, biofabrication, and smart orthotic devices embedded with sensors, could further enhance patient care. These innovations have the potential to provide real-time feedback on gait, pressure distribution, and rehabilitation progress, improving treatment outcomes. As research continues, interdisciplinary collaboration between engineers, medical professionals, and material scientists will be essential in refining 3D-printed orthoses to maximize their benefits for patients [18].

CONCLUSIONS

3D printing presents a promising future for orthotic development, offering personalized, cost-effective, and efficient solutions for patients. While challenges persist, ongoing research and technological advancements are likely to address existing limitations, paving the way for broader clinical adoption and improved patient care.

REFERENCES

1. Brachet A, Bełżek A, Furtak D, Geworgjan Z, Tulej D, Kulczycka K, Karpiński R, Maciejewski M, Baj J. Application of 3D Printing in Bone Grafts. Cells. 2023 Mar 10;12(6):859. doi: 10.3390/cells12060859. DOI
2. Abdullah KA, Reed W. 3D printing in medical imaging and healthcare services. J Med Radiat Sci. 2018 Sep;65(3):237-239. doi: 10.1002/jmrs.292 DOI
3. Ten Kate J, Smit G, Breedveld P. 3D-printed upper limb prostheses: a review. Disabil Rehabil Assist Technol. 2017 Apr;12(3):300-314. doi: 10.1080/17483107.2016.1253117. DOI
4. Ackland DC, Robinson D, Redhead M, Lee PVS, Moskaljuk A, Dimitroulis G. A personalized 3D-printed prosthetic joint replacement for the human temporomandibular joint: From implant design to implantation. J Mech Behav Biomed Mater. 2017 May;69:404-411. Epub 2017 Feb 6. doi: 10.1016/j.jmbbm.2017.01.048. DOI
5. Liaw CY, Guvendiren M. Current and emerging applications of 3D printing in medicine. Biofabrication. 2017 Jun 7;9(2):024102. doi: 10.1088/1758-5090/aa7279. DOI
6. Aimar A, Palermo A, Innocenti B. The Role of 3D Printing in Medical Applications: A State of the Art. J Healthc Eng. 2019 Mar 21;2019:5340616. doi: 10.1155/2019/5340616. DOI
7. Morrison RJ, Hollister SJ, Niedner MF, et al. Mitigation of tracheobronchomalacia with 3D-printed personalized medical devices in pediatric patients. Sci Transl Med. 2015 Apr 29;7(285):285ra64. doi: 10.1126/scitranslmed.3010825. Erratum in: Sci Transl Med. 2015 May 13;7(287):287er4. doi: 10.1126/scitranslmed.aac4749. DOI
8. Zuniga J, Katsavelis D, Peck J, Stollberg J, Petrykowski M, Carson A, Fernandez C. Cyborg beast: a low-cost 3d-printed prosthetic hand for children with upper-limb differences. BMC Res Notes. 2015 Jan 20;8:10. doi: 10.1186/s13104-015-0971-9 DOI
9. Asadi Dereshgi H, Dal H, Demir D. Türe NF Orthoses: A Systematic Review. J Smart Syst Res. 2021;2(2):135-149.
10. Akashi K. General View of Orthoses. Top Stroke Rehabil. 2004;11:3, 1-2. doi:10.1310/M7KK-UTJ8-BUHQ-FU58 DOI
11. Choo YJ, Boudier-Revéret M, Chang MC. 3D printing technology applied to orthosis manufacturing: narrative review. Ann Palliat Med 2020;9(6):4262-4270. doi:10.21037/apm-20-1185 DOI
12. Walker KJ, Przestrzelski BT, Kaluf B, et al. Novel 3D-printed foot orthoses with variable hardness: A comfort comparison to traditional orthoses. Med Eng Phys. 2023 May;115:103978. doi:10.1016/j.medengphy.2023.103978. DOI
13. Xu R, Wang Z, Ma T, Ren Z, Jin H. Effect of 3D Printing Individualized Ankle-Foot Orthosis on Plantar Biomechanics and Pain in Patients with Plantar Fasciitis: A Randomized Controlled Trial. Med Sci Monit. 2019;25:1392-1400. doi:10.12659/MSM.915045 DOI
14. Ho M, Nguyen J, Heales L, Stanton R, Kong PW, Kean C. The biomechanical effects of 3D printed and traditionally made foot orthoses in individuals with unilateral plantar fasciopathy and flat feet. Gait Posture. 2022 Jul;96:257-264. doi:10.1016/j.gaitpost.2022.06.006 DOI
15. Sanz-Pena I, Arachchi S, Halwala-Vithanage D, et al. Characterising the Mould Rectification Process for Designing Scoliosis Braces: Towards Automated Digital Design of 3D-Printed Braces. Applied Sciences 2021;11(10):4665. doi:10.3390/app11104665 DOI
16. Reymus M, Hickel R, Keßler A. Accuracy of CAD/CAM-fabricated bite splints: milling vs 3D printing. Clin Oral Investig. 2020 May 21;24(12):4607-4615. doi:10.1007/s00784-020-03329-x DOI
17. Kumar R, Sarangi SK. 3D-Printed Orthosis: A Review on Design Process and Material Selection for Fused Deposition Modeling Process. In: Patnaik A, Kozeschnik E, Kukshal V (eds). Advances in Materials Processing and Manufacturing Applications. iCADMA 2020. Lecture Notes in Mechanical Engineering. Springer, Singapore, 2021. doi:10.1007/978-981-16-0909-1_55 DOI
18. Barrios-Muriel J, Romero-Sánchez F, Alonso-Sánchez FJ, Rodríguez Salgado D. Advances in Orthotic and Prosthetic Manufacturing: A Technology Review. Materials 2020; 13(2):295. doi:10.3390/ma13020295 DOI
19. Munoz-Guijosa JM, Zapata Martínez R, Martínez Cendrero A, Díaz Lantada A. Rapid Prototyping of Personalized Articular Orthoses by Lamination of Composite Fibers upon 3D-Printed Molds. Materials 2020;13(4):939. doi:10.3390/ma13040939 DOI
20. Chalgham A, Ehrmann A, Wickenkamp I. Mechanical Properties of FDM Printed PLA Parts before and after Thermal Treatment. Polymers 2021;13(8):1239. doi:10.3390/polym13081239 DOI
21. Mian SH, Abouel Nasr E, Moiduddin K, Saleh M, Alkhalefah H. An Insight into the Characteristics of 3D Printed Polymer Materials for Orthoses Applications: Experimental Study. Polymers 2024;16(3):403. doi:10.3390/polym16030403 DOI
22. Sedigh A, Kachooei AR, Beredjiklian PK, Vaccaro AR, Rivlin M. Safety and Efficacy of Casting during COVID-19 Pandemic: A Comparison of the Mechanical Properties of Polymers Used for 3D Printing to Conventional Materials Used for the Generation of Orthopaedic Orthoses. Arch Bone Jt Surg. 2020 Apr;8(Suppl 1):281-285. doi:10.22038/abjs.2020.44038.2204 DOI

CONFLICT OF INTEREST

The Authors declare no conflict of interest.

CORRESPONDING AUTHOR
Marta Żerebiec
Student Scientific Association
at the Department of Rehabilitation and Orthopedics
Medical University of Lublin
Lublin, Poland
e-mail: zerebiecm22@gmail.com

ORCID AND CONTRIBUTIONSHIP
Aleksandra Bełżek: 0000-0001-5543-877X A B D
Marta Żerebiec: 0009-0003-7438-238X B D
Natalia Saj: 0009-0006-3069-6573 B D
Zuzanna Rupeć: 0009-0001-3767-5090 B D
Paweł Kamiński: 0009-0003-9322-6374 B D
Mateusz Kaczmarski: 0009-0000-9215-5656 B D
Karolina Turżańska: 0000-0001-7359-9622 D E F

A – Work concept and design, B – Data collection and analysis, C – Responsibility for statistical analysis, D – Writing the article, E – Critical review, F – Final approval of the article

RECEIVED: 10.11.2024
ACCEPTED: 25.02.2025