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Systematic review of customized 3D printing for pediatric fracture immobilization

Revisión sistemática sobre la impresión 3D personalizada para inmovilización de fracturas pediátricas

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Abstract

The study analyzed recent scientific evidence on the application of personalized three-dimensional (3D) printing in the immobilization of pediatric fractures, using a systematic review with a qualitative approach based on the PRISMA methodology, which used scientific articles from the last 10 years from scientific databases, obtaining 26 studies for analysis. The results showed that this technology offered an innovative alternative to conventional methods, allowing anatomically accurate, lightweight, and comfortable immobilization for children. Several studies demonstrated improvements in skin ventilation, hygiene, aesthetic acceptance, and functional recovery, reducing complications associated with the use of traditional casts. In addition, it was identified that 3D printing has not only clinical applications, but also educational and surgical planning applications, strengthening the integration between medicine, engineering, and digital technology. However, limitations were noted related to the lack of standardization, production costs, and the need for clear regulatory frameworks for its safe implementation. In conclusion, customized 3D printing has established itself as a promising tool for pediatric orthopedics, with the potential to transform traditional therapeutic approaches toward more personalized, efficient, and sustainable models, provided that research continues into its clinical validation and regulatory integration into healthcare systems.

Keywords: 3D printing, fractures, pediatrics

Resumen

El estudio analizó la evidencia científica reciente sobre la aplicación de la impresión tridimensional (3D) personalizada en la inmovilización de fracturas pediátricas, mediante una revisión sistemática con enfoque cualitativo basada en la metodología PRISMA en la cual se utilizó artículos científicos de los últimos 10 años de bases de datos científicas , obteniendo 26 estudios para el análisis. Los resultados evidenciaron que esta tecnología ofreció una alternativa innovadora a los métodos convencionales, al permitir una inmovilización anatómicamente precisa, ligera y cómoda para los niños. Diversos estudios demostraron mejoras en la ventilación cutánea, la higiene, la aceptación estética y la recuperación funcional, reduciendo complicaciones derivadas del uso de yesos tradicionales. Además, se identificó que la impresión 3D no solo tiene aplicaciones clínicas, sino

también pedagógicas y de planificación quirúrgica, fortaleciendo la integración entre medicina, ingeniería y tecnología digital. Sin embargo, se advirtieron limitaciones relacionadas con la falta de estandarización, los costos de producción y la necesidad de marcos normativos claros para su implementación segura. En conclusión, la impresión 3D personalizada se consolidó como una herramienta prometedora para la ortopedia pediátrica, con el potencial de transformar los enfoques terapéuticos tradicionales hacia modelos más personalizados, eficientes y sostenibles, siempre que se continúe investigando su validación clínica y su integración regulatoria en los sistemas de salud.

Palabras clave: impresión 3D, fracturas, pediatría

Introduction

The immobilization of fractures is a fundamental aspect of orthopedic treatment, particularly among pediatric populations, where bone fragility due to growth and high levels of physical activity increase the incidence of musculoskeletal injuries. Traditional methods, such as the use of casts or conventional splints, effectively stabilize bones; however, they have significant limitations concerning comfort, hygiene, skin ventilation, and anatomical precision. Three-dimensional (3D) printing has emerged as a technological alternative that offers customized options tailored to the patient's anatomy, enhancing comfort and optimizing the recovery process.

In the past decade, the evolution of 3D printing has simplified the custom fabrication of orthopedic supports, utilizing models that conform to the body, lightweight designs that facilitate ventilation, and biocompatible materials, all directed at the specific needs of each individual. Despite this advancement, there remains a scarcity of studies demonstrating the efficacy, durability, and overall value of these technologies, particularly in the pediatric domain. Questions persist regarding the strength of the materials, ease of use, acceptance by children and caregivers, and their integration into healthcare services. This highlights the critical need to analyze existing research to understand the current state and the challenges that must be addressed to encourage broader use in the management of fractures in children.

The rise of 3D printing in orthopedics is attributed to its ability to combine digital precision, anatomical customization, and environmental awareness in medical practice. The capacity to create immobilizers that fit like a glove to the shape of the affected limb significantly minimizes the risk of skin issues, enhances air circulation, and simplifies the cleaning of the apparatus—an essential factor for children, who often struggle to maintain traditional casts in optimal condition. Furthermore, the comfort and aesthetic appeal of 3D-printed devices promote adherence to treatment protocols, contributing to an overall improved patient experience. For institutions, this also presents an opportunity to optimize the use of available resources, accelerate rehabilitation, and move toward more personalized and effective healthcare systems.

The scientific literature presents encouraging results. Cano et al. (2021) documented the clinical use of 3D models in surgical planning and the customization of orthopedic devices, while Xu et al. (2025) demonstrated that 3D-printed splints offer advantages in ventilation, weight, and aesthetic acceptance compared to conventional casts. Chen et al. (2017) reported improved device adaptation and greater family satisfaction among pediatric patients, along with a decrease in functional recovery time. However, most available studies focus on isolated experiences or small sample sizes, underscoring the need for comprehensive and systematic reviews that consolidate findings and guide future research toward the clinical validation of this technology.

The aim of this study is to expand the existing knowledge regarding new technologies being applied in pediatric orthopedics and provide a starting point for future studies and innovations within the field of medicine.

Methodology

This study was conducted as a qualitative literature review aimed at analyzing and synthesizing recent scientific evidence regarding the application of three-dimensional (3D) printing in the immobilization of fractures in pediatric populations. The central objective was to identify technological advancements, clinical benefits, observed limitations, and future perspectives of this technique within pediatric orthopedics. To ensure the validity and reliability of the results, the review process was carried out following the methodological guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, adapted to the qualitative focus of the study.

The research adopted a systematically oriented review design, supported by the search, selection, and critical analysis of studies published over the past decade, specifically from 2015 to 2025. This design facilitated the integration of findings from various sources and methodological approaches, aiming to construct a comprehensive, up-to-date, and contextualized view of the role of 3D printing in pediatric orthopedics.

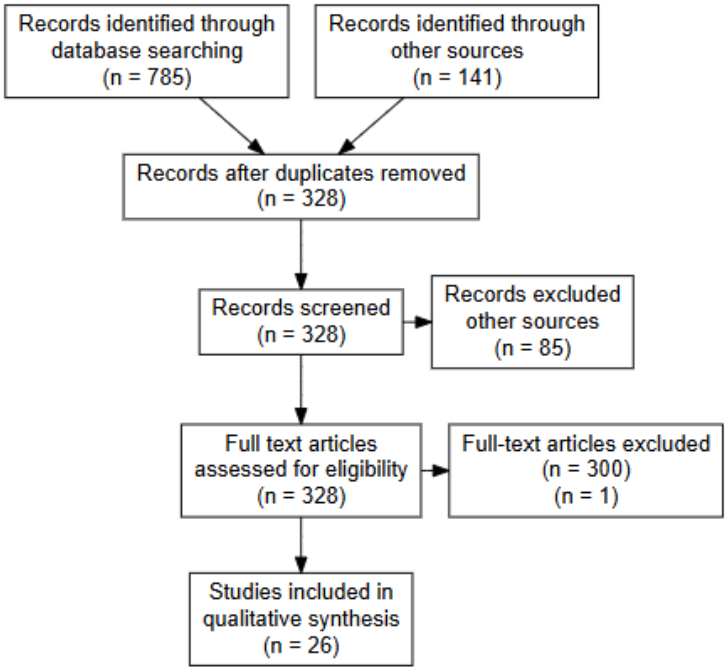
The literature search was performed in reputable and widely recognized scientific databases, including PubMed, ScienceDirect, SciELO, and SpringerLink. To optimize the identification of relevant studies, controlled descriptors in both Spanish and English were employed, combined using Boolean operators. Key terms included "3D printing," "custom immobilization," "pediatric fractures," "orthopedic splint," "additive manufacturing in orthopedics," "férulas impresas en 3D," and "fracturas pediátricas."

The application of the PRISMA methodology allowed for a structured search process consisting of clearly defined phases: identification, screening, eligibility, and inclusion. In the first phase, potentially relevant articles were gathered; in the second phase, duplicates and publications not meeting basic criteria were removed; in the third phase, titles and abstracts were reviewed to assess their pertinence; finally, full texts that aligned with the study's objectives were selected. Each selected publication underwent analytical reading, and relevant data was extracted regarding study design, participant population, type of intervention, primary outcomes, and conclusions.

Inclusion criteria: Articles published between January 2015 and September 2025; original studies, systematic or narrative reviews, case reports, and technology review articles related to 3D printing applied to orthopedic immobilization or rehabilitation in pediatric settings; publications in Spanish or English; studies involving pediatric populations (ages 0–18) or, if necessary, relevant comparisons extrapolable to the pediatric context; documents that described clinical, technical, or material aspects associated with the design, fabrication, or evaluation of 3D-printed splints.

Exclusion criteria: Articles older than 10 years; publications lacking full-text access or containing insufficient information for analysis; studies focused exclusively on surgical or prosthetic applications without relevance to immobilization; duplicate documents, brief communications, conference abstracts, and non-scientific literature; studies conducted solely in adult or animal populations.

Figure 1
PRISMA methodology



Results

Table 1
Information sources

No.	Author	Contribution to research
1	(Khorsandi et al., 2021)	Analyzed techniques and materials used in 3D and 4D printing in maxillofacial surgery, demonstrating that polymer choice directly influenced the biocompatibility

		and rigidity of the device. This finding is relevant for designing safe and ergonomic pediatric splints.
2	(Calderone et al., 2024)	Conducted a systematic review on the application of 3D printing in pediatric orthopedic surgery, concluding that this tool enhanced surgical outcomes and the quality of immobilizations. They also emphasized the need for standardized protocols for clinical use.
3	(Tsai & Greene, 2024)	Analyzed 3D printing in general pediatric surgery, noting that its application reduced operative risks and optimized preoperative planning. This study provided a global perspective on the therapeutic value of the technology for pediatric populations.
4	(Higgins et al., 2025)	Conducted a clinical study demonstrating that 3D-printed casts improved function and patient satisfaction among those with stable fractures. Results evidenced the effectiveness of three-dimensional immobilization compared to conventional methods.
5	(Matteson et al., 2025)	Compared the effectiveness of 3D-printed orthoses with traditional immobilization methods in pediatric distal radius fractures, demonstrating superiority in comfort, hygiene, and patient satisfaction. Findings provided both quantitative and qualitative evidence regarding clinical effectiveness.
6	(Xu et al., 2025)	Conducted a clinical study on the use of 3D-printed splints combined with finite element analysis for treating pediatric distal radius fractures. Results showed significant biomechanical improvements and reduced pressure in critical areas, providing evidence for optimized splint design through computational simulation.
7	(Benady et al., 2025)	Conducted a comprehensive review on advancements in 3D printing in pediatric orthopedics, concluding that custom splints and molds improved bone immobilization, reduced skin complications, and optimized functional recovery in children with fractures.
8	(Chen et al., 2017)	Applied personalized 3D-printed casts for treating distal radius fractures, observing significant benefits in ventilation, lightness, and comfort. This study represented one of the first clinical experiences validating the use of personalized three-dimensional splints.
9	(Vukicevic et al., 2017)	Analyzed the development of 3D printing in cardiology, and though their focus was different, their work provided methodological foundations that demonstrated the evolution of technology toward specific clinical applications, including pediatric orthopedics.
10	(Hui et al., 2025)	Evaluated the use of 3D templates in treating tibial epiphyseal fractures in pediatric patients, concluding that this technique reduced surgical errors and improved bone alignment. The study reinforced the clinical precision of personalized devices.
11	(Naehan & Volkan, 2024)	Reviewed the applications of 3D printing in pediatric dentistry, highlighting its ability to create anatomically precise and patient-tailored models. Their analysis demonstrated the versatility and adaptability of this technology in various pediatric medical fields.
12	(Bellia-Munzon et al., 2020)	Demonstrated that three-dimensional reconstruction facilitated surgical planning and reduced operative risks in complex pediatric procedures. Their study confirmed the utility of 3D printing as a tool that translates diagnostic precision into personalized clinical practice.
13	(Gobbato et al., 2022)	Developed a practical guide on planning and 3D printing in orthopedics, detailing technical steps from medical imaging acquisition to model fabrication. This work served as a methodological reference for creating personalized splints.
14	(Yang et al., 2021)	Conducted a meta-analysis on the applications of 3D printing in traumatic fractures, concluding that technology improved clinical outcomes, reduced surgical times, and increased patient satisfaction. Their results reinforced the validity of using 3D printing in pediatric traumatology.
15	(Mantrana et al., 2018)	Explored the use of three-dimensional models in surgical planning and teaching for mandibular fractures, highlighting their predictive and educational value. Their work validated the use of printed models as a teaching tool and for anatomical precision.
16	(Cano et al., 2021)	Described the role of orthopedic surgeons in 3D printing and analyzed the ethical and legal aspects associated with its implementation. Their research provided a regulatory

		framework supporting the safe and responsible use of personalized splints in pediatric patients.
17	(Ianno et al., 2024)	Reviewed the development of pediatric formulations through 3D printing by extrusion, emphasizing the technology's ability to adapt to the anatomical and physiological characteristics of the patient. Their investigation expanded understanding of biomedical personalization applied to children.
18	(Van Lieshout et al., 2022)	Conducted a systematic review on the use of 3D printed splints for the forearm, demonstrating clinical equivalence with conventional casts but with advantages in comfort, lightness, and aesthetic appeal. This study represented a fundamental reference for the use of 3D printing in pediatric immobilization.
19	(Broggi-Angulo et al., 2023)	Presented a clinical case where planning and 3D printing were essential in pediatric facial reconstruction, demonstrating the technology's precision and speed in treating complex fractures. Their clinical experience reinforced the viability of anatomically adapted splints.
20	(Ahmed et al., 2024)	Evaluated the use of personalized 3D printing in developing pediatric medications, providing evidence of the technology's safety and adaptability in pediatric care. Although focused on pharmacology, their research highlighted the potential of 3D printing to create tailored solutions based on each patient's physiological characteristics.
21	(Agarwal et al., 2022)	Analyzed the application of three-dimensional printing in foot fractures and deformities, demonstrating that this technology enabled greater anatomical precision and the fabrication of customized immobilization devices. Their study evidenced that 3D printed casts improved fit and patient comfort compared to traditional immobilization methods.
22	(Raza et al., 2021)	Conducted a systematic review on 3D printing in pediatric osteotomies, concluding that its use improved surgical precision and reduced recovery times. Their evidence was extrapolable to customized bone immobilization in childhood fractures.
23	(Katt et al., 2020)	Described two clinical cases where personalized 3D-printed splints were used for upper limb fractures in children. Results showed greater comfort, better hygiene, and quicker recovery, confirming the practical benefits of the personalized approach.
24	(Goetstouwers et al., 2022)	Reviewed the use of 3D printing in pediatric orthopedic surgery, highlighting its value in the fabrication of surgical guides and personalized devices. Their analysis confirmed the feasibility of integrating printed splints into conservative treatment strategies for pediatric fractures.
25	(Garay et al., 2024)	Documented a series of cases in orthopedics where 3D-printed models were used, demonstrating their utility in both surgical planning and medical education. Their work showcased the versatility of 3D printing in the field of pediatric orthopedics and traumatology.
26	(Moya et al., 2022)	Described the implementation of preoperative planning and 3D printing in orthopedics, showing a positive impact on decision-making and treatment precision. Their methodological contribution supported the personalization of pediatric devices and splints.

Discussion

The analysis of the scientific literature reveals that personalized three-dimensional (3D) printing represents a significant advancement in the immobilization of pediatric fractures by integrating anatomical precision, comfort, and safety into orthopedic treatment. The reviewed studies converged on the conclusion that the application of this technology improved the quality of immobilization and patient satisfaction while reducing skin complications and recovery times. These findings support the hypothesis that 3D printing offers an effective alternative to conventional methods, owing to its ability to reproduce specific anatomical structures tailored to pediatric patients.

In comparison with traditional approaches, the analyzed research demonstrated a clear trend toward the clinical and functional superiority of 3D-printed devices. While conventional casts exhibited limitations in ventilation, hygiene, and ergonomics, three-dimensional splints provided lightness, breathability, and anatomical fit that promoted early mobility. This pattern is consistent with findings from Higgins et al. (2025) and Matteson et al. (2025), who showed that personalized devices not only enhanced comfort but also facilitated functional

recovery. In this regard, the results align with the theory of adaptive biomedical design, which posits that structural personalization improves tissue physiological responses during rehabilitation.

From a methodological perspective, the review highlighted the importance of computational simulation and finite element analysis as complementary tools in optimizing splint designs. Studies by Xu et al. (2025) and Calderone et al. (2024) demonstrated that these methods contribute to the biomechanical validation of models, ensuring uniform pressure distribution and reducing the risk of compression injuries. These findings align with modern orthopedic engineering principles, which prioritize the integration of digital modeling and additive manufacturing to ensure reproducible clinical outcomes.

Moreover, there is consensus in the literature regarding the utility of 3D printing not only as a therapeutic technique but also as a resource for surgical planning and medical education. Contributions from Garay et al. (2024) and Bellia-Munzon et al. (2020) emphasized the pedagogical role of three-dimensional models, facilitating an understanding of anatomy and simulation of procedures, thus enhancing clinical decision-making capabilities in pediatric contexts. This versatility reinforces the relevance of 3D printing as a cross-cutting tool across education, medical practice, and technological innovation.

However, some authors noted limitations related to the standardization of clinical protocols, production costs, and the need for regulatory validation. Calderone et al. (2024) and Cano et al. (2021) pointed out that the absence of universal guidelines hampers the routine implementation of printed splints, especially in hospital settings with limited resources. This aspect reflects the existing gap between technological development and clinical application, underscoring the need for the establishment of normative and ethical frameworks that support the safe use of these technologies in pediatric patients.

Furthermore, there is a progressive diversification of medical applications for 3D printing, extending from orthopedics to areas such as pediatric dentistry and pharmacology. Research by Ahmed et al. (2024) and Naehan and Volkan (2024) highlighted that three-dimensional customization allowed for the adaptation of treatments and formulations to the physiological characteristics of children, thereby broadening the therapeutic scope of the technology. This trend supports the hypothesis that 3D printing serves as a tool for personalized medicine, with the potential to transform traditional paradigms of pediatric care.

The findings reviewed underscore the scientific and practical relevance of using personalized 3D printing in the immobilization of pediatric fractures. The integration of engineering, medicine, and digital design has led to safer, more functional, and aesthetically acceptable solutions for patients and their families. While regulatory and logistical challenges persist, the accumulated evidence demonstrates that 3D printing provides a viable alternative based on principles of biocompatibility, sustainability, and clinical precision. Its future application will depend on the establishment of standardized protocols and the strengthening of interdisciplinary collaboration between biomedical engineers and orthopedic specialists.

Conclusions

This study established that personalized three-dimensional printing represents a high-precision resource with direct implications for modernizing pediatric orthopedic treatment. Its value lies in the capacity to integrate science, technology, and medicine to offer solutions tailored to the anatomical and functional needs of each patient. Additionally, this tool fosters a new vision of clinical practice, oriented toward therapeutic personalization and technical sustainability. Ultimately, it is acknowledged that future research should focus on the clinical and regulatory validation of this technology to consolidate its safe and effective incorporation into pediatric settings.

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