3D PRINTING FOR PEDIATRIC FOOT ORTHOSES: CURRENT APPLICATIONS, CHALLENGES, AND FUTURE PERSPECTIVES

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ABSTRACT. Pediatric foot deformities such as flexible flatfoot, clubfoot, and neuromuscular-related deformities can alter plantar loading, gait, and physical activity levels. Orthoses are widely used, but pediatric care requires frequent remakes during growth, and comfort strongly affects adherence. Additive manufacturing enables a digital workflow in which foot geometry is captured by three-dimensional scanning and translated into computer-aided design. Insoles, footwear components, or ankle-foot orthoses can then be fabricated with controlled geometry and regional stiffness. This review presents current applications of 3D-printed pediatric foot orthoses, synthesizing reported biomechanical outcomes and patient-reported experience across major indications. Available studies suggest that 3D-printed devices can achieve outcomes comparable to traditional orthoses in selected pediatric groups, with potential practical benefits such as lighter structures and better perceived fit in some reports. However, evidence is limited by small samples, short follow-up, and inconsistent reporting of design parameters and outcome measures. Future studies should report designs in a reproducible way and confirm durability, adherence, and clinical benefit through longer follow-up.

KEY WORDS: 3D printing, pediatric orthoses, foot deformities, insoles, ankle-foot orthoses

ORTEZE PLANTARE PEDIATRICE IMPRIMATE 3D: APLICAȚII ACTUALE, PROVOCĂRI ȘI PERSPECTIVE VIITOARE

REZUMAT. Deformările piciorului la copii, precum piciorul plat flexibil, piciorul strâmb congenital și deformările asociate afecțiunilor neuromusculare, pot modifica încărcarea plantară, mersul și nivelul de activitate fizică. Ortezele sunt utilizate pe scară largă, însă îngrijirea pediatrică necesită refaceri frecvente pe măsură ce copilul crește, iar confortul influențează puternic aderența. Fabricarea aditivă oferă o alternativă digitală, în care geometria piciorului este captată prin scanare tridimensională și transpusă în proiectare asistată de calculator. Se pot fabrica apoi branțuri, componente de încălțăminte sau orteze gleznă-picior cu geometrie controlată și rigiditate regională. Această revizuire prezintă aplicațiile actuale ale ortezelor plantare pediatrice imprimate 3D, sintetizând rezultatele biomecanice raportate și experiența relatată de pacient pentru principalele indicații. Studiile disponibile sugerează că dispozitivele imprimate 3D pot obține rezultate comparabile cu ortezele tradiționale la anumite grupuri pediatrice, cu potențiale beneficii practice precum structuri mai ușoare și o potrivire percepută mai bună în unele rapoarte. Totuși, dovezile sunt limitate de eșantioanele mici, monitorizarea pe termen scurt și raportarea neuniformă a parametrilor de proiectare și a măsurilor rezultate. Viitoarele studii ar trebui să raporteze designurile într-un mod reproductibil și să confirme durabilitatea, aderența și beneficiul clinic printr-o monitorizare mai îndelungată.

CUVINTE CHEIE: imprimare 3D; orteze pediatrice; deformări ale piciorului; branțuri; orteze gleznă-picior

ORTHÈSES PLANTAIRES PÉDIATRIQUES IMPRIMÉES EN 3D : APPLICATIONS ACTUELLES, DÉFIS ET PERSPECTIVES FUTURES

RÉSUMÉ. Les déformations du pied chez l'enfant, telles que le pied plat flexible, le pied bot et les déformations liées à des atteintes neuromusculaires, peuvent modifier les charges plantaires, la marche et le niveau d'activité physique. Les orthèses sont largement utilisées, mais les soins pédiatriques nécessitent des réajustements fréquents au fur et à mesure de la croissance de l'enfant, et le confort influence fortement le choix de l'orthèse. La fabrication additive offre une alternative numérique, dans laquelle la géométrie du pied est captée par numérisation 3D puis traduite en conception assistée par ordinateur. Il est ainsi possible de fabriquer des semelles, des composants de chaussures ou des orthèses cheville-pied à géométrie et rigidité localisée contrôlées. Cet article présente les applications actuelles des orthèses plantaires pédiatriques imprimées en 3D, en synthétisant les résultats biomécaniques publiés et l'expérience des patients pour les principales indications. Les études disponibles suggèrent que les dispositifs imprimés en 3D pourraient offrir des résultats comparables aux orthèses traditionnelles chez certains groupes d'enfants, avec des avantages pratiques potentiels tels que des structures plus légères et un meilleur ajustement perçu, selon certains rapports. Cependant, ces données sont limitées par la petite taille des échantillons, le court terme du suivi et l'hétérogénéité des données rapportées concernant les paramètres de conception et les mesures des résultats. Les études futures devraient présenter les conceptions de manière reproductible et confirmer la durabilité, l'adhérence et le bénéfice clinique grâce à un suivi plus long.

MOTS CLÉS : impression 3D ; orthèses pédiatriques ; déformations du pied ; semelles ; orthèses cheville-pied

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INTRODUCTION

In a birth cohort, 4.2% of newborns had identifiable foot deformities [1]. Pediatric foot deformities commonly prompt orthopedic referral and may present with gait concerns or malalignment at the knee, such as genu varum or valgum [2, 3]. Flexible pes planovalgus is common in early childhood and often improves as the medial arch develops [4, 5]; when pain or functional limitation persists, conservative measures may include stretching or physiotherapy and in-shoe orthoses [2, 6–8]. Congenital conditions such as clubfoot require early treatment, and serial casting followed by bracing can avoid surgery in most cases [1, 2, 9, 10]. Cavovarus or equinus patterns may signal neuromuscular diseases such as Charcot-Marie-Tooth (CMT) neuropathy or cerebral palsy (CP); orthoses, casting, and botulinum toxin can be used to improve dorsiflexion and gait [2, 11–14]. Across this diverse clinical spectrum, orthotic management plays a central role in conservative treatment strategies.

Custom foot orthoses (FOs) and ankle-foot orthoses (AFOs) are still commonly fabricated from negative impressions with subsequent rectification and thermoforming [15–17]. The process is labor-intensive and often must be repeated as children outgrow devices [16, 18]. In children prescribed AFOs, 3D scanning has been reported to be faster than plaster casting and can achieve high measurement accuracy when appropriate scanners and protocols are used [18]. Additive manufacturing (AM) can reproduce devices from stored digital models and facilitates targeted changes to thickness, trim lines, and internal structures such as lattices [16, 19]. Comfort and appearance are important determinants of acceptability and adherence, including in Charcot-Marie-Tooth disease [19–21]. Reported pediatric applications include printed insoles for symptomatic flexible flatfoot, printed AFOs for Charcot-Marie-Tooth disease, and printable braces used in clubfoot management [22, 23]. However, existing reviews note limited and heterogeneous evidence across designs and outcomes, indicating the need for a focused synthesis in pediatric foot orthoses [19].

This review summarizes current evidence on 3D printing in pediatric foot orthoses. We examine the literature by common indications, including flexible flatfoot, clubfoot, and neuromuscular-related deformities, and describe approaches to device design and fabrication within a digital workflow. We then compare printed and traditionally manufactured orthoses with respect to reported clinical and biomechanical outcomes, comfort and adherence, and practical considerations. Finally, we discuss key challenges and future research directions related to materials and manufacturing, variability in clinical effectiveness, and clinical implementation of 3D-printed pediatric foot orthoses.

ADDITIVE MANUFACTURING OF PEDIATRIC FOOT ORTHOSES

Digital Workflow

Additive manufacturing (AM) enables pediatric orthoses to be produced within a digital workflow that includes scanning, computer-aided design (CAD), and printing, rather than plaster casting and manual rectification [24–26]. As shown in Figure 1, pediatric orthoses can be produced through a scan, CAD, slicing, printing, and fitting workflow, replacing plaster casting and manual rectification in many cases. Geometry can be captured using structured light, laser, or photogrammetry-based scanners and exported as surface meshes (e.g., STL or OBJ) for orthosis design [27, 28]. For pediatric AFO fabrication, comparisons indicate that scanning can capture clinical geometry faster than casting when standardized protocols are applied [18]. The capture condition should be specified, including weight-bearing status and intended alignment, because posture during acquisition influences final orthosis geometry [27, 29]. After scanning, mesh processing such as cleanup, landmark identification, and boundary definition is typically required before computer-aided design modification, and this step can introduce variability if workflows are not standardized [26, 30]. During design, prescriptions are translated into geometry through decisions about trim lines, thickness distribution, relief regions, and correction or alignment features [29, 31]. Parametric methods and simulation-informed approaches have been used to target stiffness and pressure distribution before fabrication and may reduce the need for repeated refitting [32–34]. Slicing converts the model into toolpaths, and print settings, including orientation, layer height, and infill, influence mechanical behavior [35, 36]. Clinical case reports demonstrate that end-to-end digital pipelines are feasible, although fitting and finishing still require clinician input [26, 37]. Post-processing commonly includes edge finishing, strap and pad integration, and dimensional checks, which are particularly important for pediatric skin tolerance and safety [26, 28]. Retaining digital models supports rapid remakes and resizing, which is clinically relevant because children grow and often require repeated refitting [38, 39]. Low-cost scanning and printing can be feasible for custom foot orthoses, but consistent outcomes depend on well-defined protocols and quality assurance [17, 27].

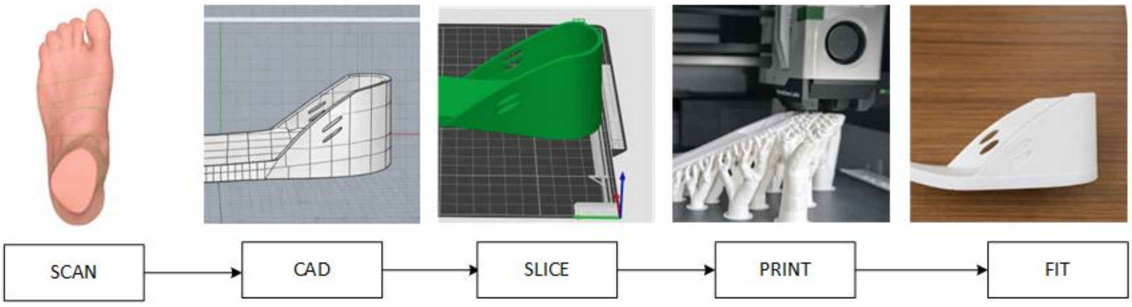


Figure 1. Digital workflow for additive manufacturing of pediatric orthoses. (Created by the authors)

Printing Technologies and Material Considerations

Polymer-based AM is most commonly used for orthoses. Frequently reported processes include fused deposition modeling or fused filament fabrication (FDM/FFF), selective laser sintering (SLS), and, less commonly, multi-jet fusion (MJF), as well as stereolithography or digital light processing (SLA/DLP) [24, 25, 40]. FDM/FFF is widely used because of accessibility and short build times, supporting prototyping and iterative development of pediatric orthosis designs [35, 41]. A key limitation is anisotropy introduced by layerwise deposition, meaning strength and stiffness depend on build orientation and print parameters [35, 42]. For insoles and foot orthoses, designers can vary infill and thickness to create region-specific stiffness, which is difficult to reproduce consistently with manual fabrication [43, 44]. Reviews of printed insoles emphasize that material selection and build strategy should match the clinical objective, such as providing support or increasing cushioning [45, 46]. SLS is used for AFOs because it can produce complex geometries without support structures and can provide favorable strength-to-weight performance in nylon parts [40, 47]. Clinical gait evaluations indicate that SLS AFOs were feasible at initial fitting and may deliver functional effects for individuals with foot drop [48, 49]. Design freedom is often used to reduce weight and improve ventilation through perforations or lattice-like regions while maintaining targeted stiffness [40, 47]. SLS and MJF can require substantial post-processing, including depowdering and surface finishing. Therefore, workflow planning should account for surface feel and edge quality, which are critical for pediatric comfort [26, 28]. SLA/DLP can deliver high resolution and smooth surfaces, but resin selection, post-curing, and long-term mechanical qualification are important when devices are intended to bear load [25, 50]. Beyond standard polymers, studies have explored bio-based polycarbonate and fiber-reinforced concepts to improve toughness or stiffness-to-weight ratio [51, 52].

Early work on AFOs indicates that the manufacturing method affects dimensional accuracy and device-to-device consistency [53]. For foot orthoses, stiffness functions as a meaningful design parameter, because changes in stiffness or posting can influence plantar pressure distribution and muscle activity [44, 54]. Randomized crossover testing suggests that printed foot orthoses can produce biomechanical effects comparable to traditionally manufactured orthoses in flexible flatfoot [45, 55]. 3D printing also facilitates the integration of sensors or instrumentation, enabling objective monitoring of parameters such as alignment, pressure, or joint angle during use [56–58]. In pediatric populations, acceptance is strongly influenced by comfort and wearability, and studies of printed casts or orthoses commonly report higher comfort or satisfaction than traditional alternatives [59–61].

CURRENT APPLICATIONS OF 3D PRINTING IN PEDIATRIC FOOT ORTHOSES

Pediatric foot deformities commonly managed with orthoses include symptomatic flexible flatfoot, idiopathic clubfoot (congenital talipes equinovarus), and neuromuscular-related deformities associated with conditions such as cerebral palsy and Charcot-Marie-Tooth disease [2, 7, 62]. Treatment goals vary across these conditions, so orthotic form and design priorities vary as well. Flexible flatfoot management focuses on symptom relief and arch support, neuromuscular disorders on gait stabilization, and clubfoot on maintenance bracing after Ponseti correction [7, 13, 62, 63]. Consistent with these needs, reported pediatric applications of 3D printing mainly focus on printed insoles for flexible flatfoot, printed ankle-foot orthoses for neuromuscular gait disorders, and printed foot-abduction orthoses or modular brace components for clubfoot management [22, 23, 64, 65].

3D-printed Insoles for Symptomatic Flexible Flatfoot

Pediatric pes planus is commonly classified as flexible or rigid. Rigid flatfoot is uncommon and should prompt evaluation for underlying structural pathology. Therefore, this section focuses on flexible flatfoot [7, 66, 67]. Flexible flatfoot presents with a low medial arch during stance, whereas the arch and hindfoot alignment are corrected in non-weight-bearing positions or on tiptoe [7, 66]. As shown in Figure 2, the medial longitudinal arch collapses during standing in flexible flatfoot deformity. In typically developing children, arch height often becomes more defined with age, and many cases are asymptomatic and self-limiting [4, 66, 67]. However, in school-aged children, symptomatic flexible flatfoot has been associated with higher pain scores and poorer health-related quality of life, and orthoses are frequently prescribed to address pain and function [68–70]. Consequently, reassurance and periodic follow-up are appropriate for asymptomatic flexible flatfoot, whereas symptomatic cases are typically managed conservatively with education, supportive footwear, stretching when equinus is present, and in-shoe orthoses when pain, fatigue, or functional limitations persist [7, 8, 66, 67]. Contemporary evidence syntheses suggest that orthoses may reduce pain and improve certain functional or radiographic outcomes in older children with symptomatic flatfoot. However, in younger children, the effects are less consistent and appear to vary depending on device design and follow-up duration [71–74].

Figure 2. Flexible flatfoot in a child, showing the collapse of the arch on standing. (Source: Wikimedia Commons, "Children flat feet" (File:Children_flatfeet.jpg), CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Children_flatfeet.jpg)

Within pediatric foot orthotics, 3D-printed insoles and other in-shoe devices represent the most frequently reported additive-manufactured application [45, 75–77]. Digitization enables a repeatable workflow in which foot geometry is captured by 3D scanning, while plantar-pressure measurements can be used to localize regions requiring medial support, offloading, or posting [31, 74, 75]. Compared with traditional milling or manual fabrication, 3D printing enables precise and repeatable tuning of orthotic stiffness by modifying arch geometry, shell thickness, and printing parameters (such as infill density, lattice design, and targeted reinforcement), while keeping the patient-specific shape constant for controlled evaluation of different support levels [43, 44, 54, 76, 77]. In pediatric flexible flatfoot, Lee *et al*. reported that pressure-based customized printed insoles were associated with measurable changes in radiographic hindfoot alignment, suggesting that digital customization can translate to objective alignment outcomes [75]. Zhao *et al*. printed multiple insole variants with different arch heights and infill densities and reported changes in center-of-pressure progression and gait-phase measures, illustrating how printing facilitates rapid prototyping across stiffness conditions (Figure 3) [76]. Early clinical evidence also suggests potential advantages in comfort and adherence, which are particularly relevant for children. In an open-access study including a 1-year follow-up of school-age children with symptomatic flexible flatfoot, Hu *et al*. compared ordinary orthopedic insoles with 3D-printed orthopedic insoles and reported longer wearing time in the 3D-printed group, alongside significant pain reduction after follow-up, highlighting comfort as a potential contributor to adherence [74]. Nevertheless, systematic reviews emphasize substantial heterogeneity across studies in scan methods, design features, materials, outcome metrics, and follow-up duration, limiting quantitative pooling and generalizability [45, 78]. Overall, the pediatric literature supports feasibility and measurable biomechanical or alignment changes, but higher-quality comparative trials with standardized clinical and patient-reported outcomes are still needed to define which design parameters provide durable benefit in specific subgroups [45, 74–76].

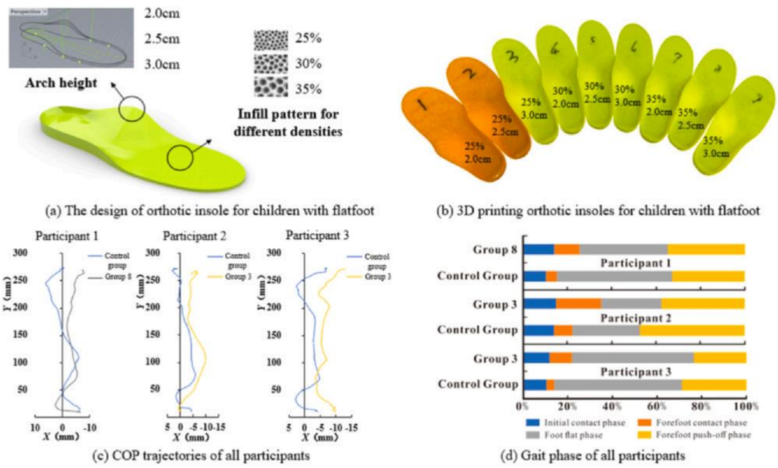


Figure 3. (a) Design of the orthotic insole based on pediatric foot arch morphology. (b) 3D printing of orthotic insoles with different arch heights and infill densities to achieve varying support stiffness. (c) Center-of-pressure (COP) trajectories of all participants during walking. (d) Gait phase characteristics of all participants. (Source: Zhao *et al*., 2023, Design and validation of 3D printed orthotic insoles for children with flatfoot, *Gait & Posture*, https://doi.org/10.1016/j.gaitpost.2023.07.275)

3D-printed Ankle Foot Orthoses for Neuromuscular-related Deformities

Neuromuscular and neuro-developmental disorders such as cerebral palsy (CP), Charcot-Marie-Tooth disease (CMT), and muscular dystrophy commonly result in secondary foot and ankle deformities and abnormal gait patterns. In these patients, ankle-foot orthoses (AFOs) and supramalleolar orthoses (SMOs) are used to stabilize the ankle, improve alignment, reduce energy expenditure, and support functional ambulation [40, 79–82]. In CMT, in-shoe orthoses may be used for symptomatic pes cavus, whereas AFOs are commonly indicated when foot drop or more pronounced gait impairment is present; however, comfort and perceived usefulness substantially influence adherence [11, 20–22, 83]. In spastic CP, orthoses are often integrated with physiotherapy, stretching/serial casting, and botulinum toxin to address equinus gait, and meta-analytic evidence suggests that orthoses can increase ankle dorsiflexion at initial contact compared with control conditions [10, 13, 84, 85]. These clinical drivers make digital design and 3D printing appealing, because devices can be resized and iteratively updated as children grow or as motor patterns evolve [22, 40]. Figure 4a illustrates equinus (toe-walking) gait commonly observed in children with spastic cerebral palsy, while Figure 4b shows the characteristic cavovarus foot deformity associated with Charcot-Marie-Tooth disease.

(a) (b)

Figure 4. (a) Toe walking (equinus gait) in a child, characterized by forefoot contact and limited heel strike during stance. (Source: Wikimedia Commons, “Zehenspitzengang unbehandelt.jpg”, CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Zehenspitzengang_unbehandelt.jpg), (b) Foot deformity in Charcot-Marie-Tooth disease, showing muscle atrophy, a high medial longitudinal arch, and hammer toes. (Source: Wikimedia Commons, “Charcot-marie-tooth_foot.jpg”, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Charcot-marie-tooth_foot.jpg).

In pediatric practice, 3D-printed foot and ankle orthoses are most commonly reported in neuromuscular gait disorders where ankle control is central, particularly spastic CP and CMT [11, 22, 64]. For children with spastic CP, Qin *et al*. retrospectively compared customized 3D-printed AFOs with traditional AFOs and reported that the printed devices were lighter and thinner (approximately 124 g vs. 183 g; 1.7 mm vs. 3.0 mm), with modest improvements in walking speed and stride length (Figure 5) [64]. For pediatric CMT, Wojciechowski *et al*. demonstrated that 3D printing can replicate traditional AFO geometry and that redesign using print-enabled structural changes produced devices that were approximately 35% lighter and improved the ankle dorsiflexor moment during loading response, highlighting the potential of digital iteration beyond simple replication [22].

Beyond these pediatric comparisons, engineering and adult clinical studies provide a methodological foundation for printed AFO development, including selective laser sintering (SLS) of nylon-based braces, objective gait and plantar-pressure assessment during fitting, and systematic exploration of stiffness effects [47–49]. Overall, current reviews suggest that 3D-printed AFOs can achieve gait effects broadly comparable to traditionally fabricated AFOs, but pediatric-specific evidence and durability/quality-assurance reporting remain limited [19, 40, 78].

Figure 5. Prototype application and integration of a 3D-printed foot/ankle orthotic system. (A) Custom-fabricated 3D-printed foot orthosis (FO) insole. (B) The insole integrated into a foot/ankle brace with metallic supportive components. (C) Lateral view of the fully assembled ankle-foot orthosis (AFO). (D) Clinical demonstration of the bilateral 3D-printed AFO system worn with standard footwear. (Source: Qin *et al*., 2025, *Frontiers in Pediatrics*, CC BY 4.0, https://doi.org/10.3389/fped.2025.1661098)

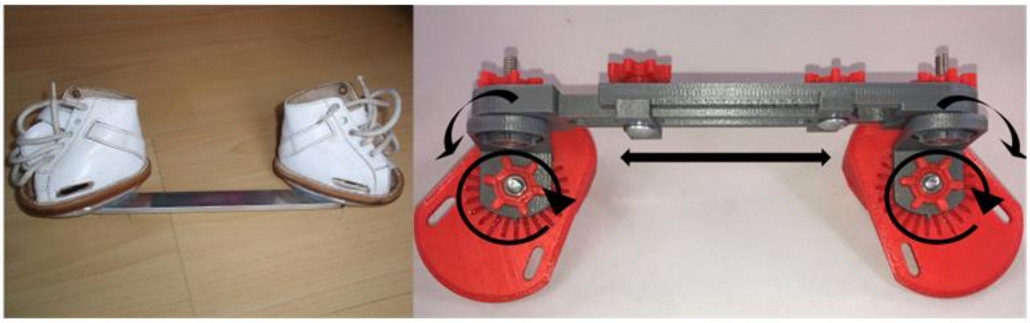
3D-printed Foot Abduction Orthoses and Brace Components for Clubfoot

Idiopathic congenital talipes equinovarus (clubfoot, CTEV) is a common congenital musculoskeletal deformity, with a corrected pooled global birth prevalence of about 1.10 per 1,000 births; regional variation is substantial, and the burden is disproportionately high in low- and middle-income settings [9, 62, 86]. Clinically, clubfoot is characterized by cavus, forefoot adduction, hindfoot varus, and equinus (Figure 6) [62, 87]. The first-line standard of care is the Ponseti method, which involves staged manipulation and serial casting. This is commonly followed by percutaneous Achilles tenotomy and prolonged foot-abduction bracing to maintain correction and reduce the need for extensive surgery [62, 63, 88–90]. Because relapse is strongly associated with poor brace adherence, the design, comfort, and usability of foot-abduction orthoses (FAOs) are clinically consequential and are a major focus of device innovation [91, 92].

Figure 6. Infant with congenital clubfoot (talipes equinovarus). The affected foot is twisted sharply inward and downward. (Source: Wikimedia Commons, CC BY 3.0, https://commons.wikimedia.org/wiki/File:813_Clubfoot.jpg)

For idiopathic clubfoot treated with Ponseti, post-correction FAO use is central to relapse prevention, and objective monitoring studies show that parent-reported brace wear can be inaccurate; lower adherence is associated with higher relapse risk [93, 94]. Traditional boots and bars reduce recurrence more effectively than ankle-foot orthoses, reinforcing the need to maintain abduction during the maintenance phase [95]. However, skin problems, discomfort, and practicality can undermine adherence, motivating alternative brace designs (e.g., dynamic FAOs) intended to improve tolerance [96]. In this context, additive manufacturing has been explored primarily as a means to improve access, fit, adjustability, and instrumentation rather than to replace the Ponseti protocol itself [23, 65, 97, 98].

An open-source 3D-printable infant clubfoot brace has been reported as a low-cost alternative that aims to preserve the functional principles of foot-abduction bracing while enabling distributed manufacturing and local replacement of components as infants grow [23]. More recently, Beldar *et al*. proposed an adjustable clubfoot splint with modular 3D-printed components, allowing correction angles and fit to be adjusted without fully remanufacturing the entire system—an approach aligned with the rapid iteration potential of digital workflows [65]. 3D printing has also enabled rapid prototyping of custom brace geometries and corrective footwear components (e.g., shoe plates, bar connectors, and adjustable interfaces), supporting iterative refinement based on clinician feedback and observed tolerance [97]. In parallel, sensor-integrated bracing concepts illustrate how additive manufacturing can be combined with remote monitoring to quantify adherence, which is a key determinant of long-term outcomes in clubfoot [98]. Overall, published reports suggest that 3D-printed FAO solutions are feasible and may improve access or adjustability, but clinical validation remains limited; relapse prevention still depends on adherence, follow-up capacity, and service delivery models, particularly in resource-constrained settings [9, 86, 91, 93].



(a) (b)

Figure 7. Examples of traditional and innovative 3D-printed FAOs for clubfoot treatment: (a) Shoes mounted on a Denis Browne bar, a foot abduction brace used in clubfoot treatment, named after British pediatric surgeon Denis Browne (Source: Wikimedia Commons, CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Botas.JPG). (b) Open-source 3D-printable infant clubfoot brace design illustrating adjustable components. (Source: Appropedia, “Open-Source Three-Dimensional Printable Infant Clubfoot Brace”, Savonen, B., Gershenson, J., Bow, J.K., Pearce, J.M., CC BY-SA 3.0, https://www.appropedia.org/Open-Source_Three-Dimensional_Printable_Infant_Clubfoot_Brace)

COMPARISON OF 3D-PRINTED VS. TRADITIONAL ORTHOSES

Clinical Effectiveness

Current evidence suggests that 3D-printed ankle-foot orthoses (AFOs) can achieve gait outcomes broadly comparable to traditional AFOs, although most studies remain small and short-term [19, 40]. In children with spastic cerebral palsy, a comparative study reported greater improvements in function and spatiotemporal gait parameters with 3D-printed AFOs than with traditional polyethylene AFOs over 3 months. In that cohort, both groups improved, but the 3D-printed group showed larger Gross Motor Function Measure (GMFM) gains (about +6.5 vs. +3.2) and larger increases in cadence and step length [64]. For pediatric neuromuscular disease, 3D printing has been used to replicate and redesign AFOs for children with Charcot-Marie-Tooth disease, enabling matched geometry and iterative modification within a single workflow [22]. For school-age children with symptomatic flexible flatfoot, 3D-printed orthopedic insoles have been reported to reduce pain at follow-up, with adherence benefits in some subgroups. A one-year follow-up study reported pain score reductions of approximately 1-2 points on a 0-10 visual analog scale and longer wearing time for 3D-printed insoles in lighter-weight children compared with traditional insoles [74]. Overall interpretations remain cautious because studies vary in materials, stiffness design, and outcome measures [45]. Traditional custom foot orthoses can already improve pain and balance in children with symptomatic flexible flatfoot, so 3D-printed devices should demonstrate similar benefits under comparable conditions [75, 99]. Clinically, printing is a manufacturing route rather than an intervention in itself, and outcomes depend on orthosis geometry and stiffness as much as on the fabrication method [40, 44].

Patient Comfort, Adherence, and Patient-reported Outcomes

Patient-reported outcomes are increasingly reported, and some AFO studies show higher satisfaction with fit and comfort for 3D-printed devices. However, outcome measures are inconsistent across studies [40, 100]. In pediatric flatfoot, comfort is clinically important because it can translate into longer daily wearing time, which is a practical prerequisite for effectiveness [74]. For bracing in infant clubfoot, low-cost 3D-printed brace concepts exist, but adherence still depends on usability, follow-up, and family support rather than printing alone [23].

Customization, Production Time, and Reproducibility

The practical advantage of additive manufacturing is greater workflow control.

Digital capture and computer-aided design make remakes and incremental resizing easier across follow-up visits [19, 24]. In pediatric AFO fabrication, structured-light scanning has been reported to be faster than plaster casting while achieving comparable shape capture under standardized protocols [18, 27]. Cost is context-dependent. An economic evaluation of wrist orthoses found higher mean costs for 3D-printed orthoses than for low-temperature thermoplastic orthoses, with labor as the main cost driver [101]. Therefore, comparisons should be condition and setting-specific. Both routes can meet similar clinical targets, while printing mainly influences reproducibility, redesign speed, and traceability [19, 26].

CHALLENGES AND FUTURE PERSPECTIVES

Materials and Manufacturing Limitations of the Orthosis

3D printing provides new possibilities for customized pediatric foot orthoses; compared with traditional plaster casting and thermoforming, it enables complex geometries, region-specific stiffness tuning, and lightweight designs [26, 27, 31, 43]. However, there are still many limitations in the orthosis materials and manufacturing processes [25, 26, 78]. Common printable materials include polylactic acid (PLA), polyamides (e.g., PA12 nylon), and thermoplastic polyurethane elastomers (TPU); their mechanical properties and biocompatibility differ [40, 78].

Current Challenges

First, evidence on the long-term durability and material robustness of 3D-printed orthoses remains limited, and durability concerns still need to be addressed [19, 78]. Wojciechowski *et al*. noted that fatigue/ durability testing is scarce in existing studies, and only a few studies performed destructive tests and compared material performance [19]. For example, some studies compared materials such as Nylon-11 and Nylon-12 and suggested better damping/deformation tolerance for Nylon-11, whereas glass-fiber-filled Nylon-12 was more prone to failure [19, 102, 103]. Second, small changes in printing parameters (e.g., layer thickness, infill density, and build orientation) can significantly alter mechanical properties, requiring empirical calibration using printed specimens rather than relying only on nominal material data [33, 104]. In addition, surface roughness and dimensional accuracy also affect skin conformity and comfort [26, 28]. 3D-printed orthoses often require post-processing (support removal, edge sanding, heat treatment, etc.) to reduce burrs and improve comfort; for photopolymer resin systems, adequate post-curing and long-term mechanical qualification are important for load-bearing devices [19, 26, 50]. Regarding biocompatibility, many polymers used for 3D-printed orthoses are industrial-grade; certification and evidence for prolonged skin contact can be limited, and irritation risks under sweat/friction may warrant further evaluation [26, 50, 78]. Overall, insufficient strength/durability, structural defects, and surface/finishing issues together constitute the core challenges of the 3D-printed orthosis body.

Future Trends

To address material and process constraints, research is moving toward higher-performance materials and design optimization. First, in terms of materials, developing and evaluating new materials will improve orthosis strength and durability [78]. For example, adopting Nylon-11 or reinforcing/compounding PLA with fibers and elastomers may help balance stiffness and toughness [51, 52, 102, 104]. Meanwhile, cyclic fatigue testing under repeated pediatric loading and biocompatibility standardization are needed to verify service life and ensure long-term contact safety [78]. For post-processing, chemical polishing and antibacterial coatings may be used to improve surface smoothness and biocompatibility, making orthoses more comfortable to wear. Second, in terms of manufacturing processes, improvements in digital design tools may help mitigate the impact of structural defects. By using simulation to optimize internal lattice structures and region-specific thickness, overall strength and durability may improve without excessive weight gain [32, 33]. In addition, modular and hybrid design strategies have been proposed to enhance practical adjustability. By introducing detachable or adjustable components, local stiffness or size can be fine-tuned without redesigning the entire device. For example, combining traditional heat-adjustable elements with 3D-printed components allows selected modules to be replaced or reprinted as needed, rather than remanufacturing the whole orthosis, thereby improving clinical flexibility [65]. Overall, future work should integrate materials science and design innovation to improve the mechanical reliability and safety of 3D-printed orthoses, providing pediatric patients with lightweight, comfortable, and durable assistive devices.

Variability in Clinical Effectiveness

Different clinical studies report substantial variability in the effectiveness of 3D-printed foot orthoses [40, 45, 100]. Some reports indicate that 3D-printed AFOs often provide better comfort and fit than traditional devices, leading to higher patient satisfaction [40, 78]. However, across populations such as pediatric flexible flatfoot, Charcot-Marie-Tooth disease (CMT), and spastic cerebral palsy, studies report inconsistent degrees of gait improvement and symptom relief [40, 45]. Daryabor *et al*. concluded in a systematic review that 3D-printed insoles may have positive effects on pain/comfort and foot function; however, reports on plantar pressure, center-of-pressure measures, and three-dimensional ankle kinematics and kinetics are inconsistent across studies [45]. For example, in children with flatfoot, some studies found that wearing customized 3D-printed insoles can reduce pain and improve walking comfort in the short-term, but findings on gait biomechanics (e.g., plantar pressure distribution and spatiotemporal parameters) are inconsistent [45, 100]. In neuromuscular populations (e.g., cerebral palsy, stroke, and CMT), 3D-printed AFOs have shown immediate improvements in selected gait parameters compared with no orthosis. Across studies, their functional effects are generally comparable to traditionally fabricated AFOs [40].

Current Challenges

First, most existing studies are limited by small sample sizes and short follow-up durations; many are single-case reports or involve fewer than 10 participants, with follow-up ranging from immediate effects to only a few weeks [40, 45, 100], leading to uncertainty about overall clinical effectiveness. In addition, heterogeneity across study populations represents an inherent challenge. Children and adults differ in neuromuscular control and adherence, and even within pediatric cohorts, unavoidable variability in deformity severity, gait patterns, and body size may influence observed outcomes. Furthermore, differences in adherence and real-world use conditions may further contribute to variability across studies. For example, some studies allow participants to wear orthoses within their usual footwear, whereas others assess gait under barefoot conditions; such differences in wearing protocols can affect gait performance and confound comparisons. Moreover, clinical benefits often require time to accumulate; short-term observation may under- or overestimate effects, and long-term follow-up is needed to evaluate arch remodeling or gait reconstruction. The current literature rarely reports long-term follow-up outcomes for 3D-printed orthoses, limiting understanding of the durability of effects and longer-term functional impact [40, 45, 78]. In summary, small sample sizes, short follow-up durations, population heterogeneity, and differences in adherence and real-world use jointly contribute to variability in reported clinical effects.

Future Trends

To reduce variability in effectiveness research, future improvements are needed in trial design and reporting standards. First, higher-quality controlled studies with larger samples and longer follow-up should be conducted to obtain statistically robust and clinically meaningful evidence. As Pollen *et al*. suggested, areas showing preliminary effectiveness urgently need rigorous randomized controlled trials with larger cohorts and long-term follow-up to confirm durability of benefits [40]. In reporting, there is a call to establish standardized outcome frameworks. Future studies should report indications, orthosis type, key design parameters (e.g., materials and stiffness distribution), printing process/settings, and follow-up schedule in detail [26]. Using unified outcome measures (e.g., standardized gait analysis protocols, plantar pressure metrics, and patient-reported outcome scales) would facilitate cross-study comparisons and meta-analyses [40, 45]. To account for individual differences, future work may integrate 3D foot data with biomechanical models to predict patient-specific gait effects of different designs. In parallel, subjective feedback and adherence data should be emphasized alongside objective measurements (e.g., pain on a visual analog scale (VAS), activity level, and wearing time) to evaluate clinical relevance comprehensively. In short, future clinical research should pursue standardization and personalization in parallel to reduce evaluation bias and clarify the value of 3D-printed orthoses for different pediatric foot conditions.

Barriers to Clinical Implementation

Although 3D printing shows promise for faster orthosis production and improved fit, real-world clinical implementation still faces multiple barriers [26, 27]. Compared with adults, pediatric patients have unique difficulties in digital shape capture and in providing feedback during orthosis use [27, 28].

Current Challenges

First, acquiring foot morphology data is difficult. Accurate foot anatomy is required for customized orthoses and is typically obtained via 3D scanning. However, young children often have difficulty keeping still during scanning. Even with fast structured-light scanners, movement can create artifacts or incomplete data, reducing downstream design accuracy [28]. In addition, the scanning posture (e.g., weight-bearing standing vs. non-weight-bearing sitting) can substantially influence the final corrective orientation of the orthosis [29]. Currently, there is no unified standard to guide pediatric foot scanning posture and protocols; data standards vary across institutions, causing downstream fabrication differences from the outset [26–28]. Second, the digital design workflow lacks standardization. After obtaining a foot model, CAD software is required for 3D modeling and modification of the orthosis. However, there is still no widely accepted pediatric foot orthosis design paradigm; technicians often rely on personal experience to adjust arch support height, shell thickness, and padding locations [26, 31]. This manual modeling process is subjective, and consistent quality is hard to guarantee across designers and software tools. Without standardized templates and parameter guidance, even the same input foot data can yield highly variable orthosis designs. Third, printing reproducibility and consistency are insufficient. Differences across printers and material batches, as well as small changes in printing parameters (temperature, speed, infill pattern, etc.), can affect orthosis hardness and dimensional accuracy [26, 104]. Without a mature quality control system, printed orthoses may vary slightly from one production run to another. Industry standards in this area have not yet been fully established [26]. Fourth, mechanisms for collecting comfort feedback are insufficient. The clinical value of orthoses is not only deformity correction but also sustained wearing and adherence. A key factor influencing wearing willingness is comfort, including whether the orthosis causes pressure pain, skin friction, or walking inconvenience [100]. Existing practice lacks systematic mechanisms for feedback collection and iterative design; it often relies on subjective reports from patients/caregivers, with long feedback cycles and incomplete information. Such an imperfect feedback system may delay identification and correction of comfort issues, thereby reducing adherence [100]. Finally, workforce and workflow bottlenecks also limit large-scale clinical adoption of 3D-printed orthoses. Clinical teams need cross-disciplinary skills in scanning, modeling, and printing, yet many orthotists and clinicians lack training opportunities. If hospitals attempt to adopt digital workflows, new collaboration models and a clear division of labor between clinical and engineering teams are also needed. Without mature workflow guidance, the expected advantages in rapid delivery may not be realized [26]. In summary, barriers in data acquisition, design standards, production consistency, feedback mechanisms, and workforce training make it challenging for 3D-printed pediatric foot orthoses to transition from laboratory exploration to routine clinical practice.

Future Trends

To promote broader clinical adoption of 3D-printed orthoses, optimization is needed on both technical and managerial levels. First, new child-friendly foot scanning solutions can be explored. For example, faster scanners or multi-view photogrammetry could reduce acquisition time and improve cooperation; for toddlers unable to stand still, lightweight adjustable fixtures may help stabilize posture during rapid scanning. For standardized scanning protocols, posture and weight-bearing requirements for different pediatric age groups, along with accuracy verification methods, should be defined to ensure reliable digital models [27, 28]. Second, regarding CAD standardization, open design databases and parameter guidelines for pediatric foot orthoses could be developed [29, 32]. By aggregating data from many clinically successful cases, optimized geometries for different conditions can be extracted to enable semi-automated design assistance. For example, software could auto-generate an initial orthosis model based on inputs such as arch height and inversion/eversion angles, allowing technicians to fine-tune it and reducing purely subjective variability. Third, printing and quality-control workflows should be optimized; healthcare institutions should adopt rigorous digital manufacturing quality management systems. This includes regular equipment calibration, material batch control, and verification of key parameter consistency. Manufacturing-style approaches can be adopted, such as adding standard test coupons to each batch to monitor whether hardness and dimensions meet requirements and to enable closed-loop adjustment when deviations occur. In addition, because children often require size adjustments during growth, future orthosis designs may reserve adjustable margins or use modular structures; when children grow or discomfort occurs, modules can be replaced or partially reprinted rather than remaking the entire device [65]. Fourth, a systematic patient feedback and follow-up mechanism should be established. Future digital health platforms could allow parents to regularly report comfort, including redness and pressure pain. These data could be linked with design parameters to help technicians identify which design features cause discomfort and improve the next iteration. Finally, workforce training and service models should be upgraded in parallel. Cross-domain training should be provided so orthotists can master basic 3D scanning and CAD skills while engineers understand foot biomechanics and clinical needs. Hospitals may establish multidisciplinary workflows, for example, rehabilitation physicians prescribe and evaluate, orthotists scan and design, engineers print and post-process, and clinicians fit and validate the device [30]. With a clear division of labor and strengthened training, the efficiency benefits of digital workflows can be fully realized. In summary, future efforts should optimize technical workflows while strengthening clinical integration: overcoming technical bottlenecks in scanning, design, and printing, and establishing patient-centered feedback loops and workforce support. Only in this way can 3D-printed pediatric foot orthoses truly move from experimental exploration to routine clinical practice and benefit more children.

CONCLUSION

3D printing enables pediatric foot orthoses to be produced through a digital workflow that improves traceability and supports efficient remakes during growth. Current pediatric studies suggest that printed insoles and ankle-foot orthoses can achieve short-term biomechanical outcomes comparable to traditionally fabricated orthoses in selected conditions, while clubfoot work mainly focuses on foot-abduction bracing and modular components. The main constraint is that the clinical evidence is still early-stage, with short follow-up and inconsistent reporting of key design and manufacturing details. Progress now depends on standardized reporting and clinical quality assurance. Longer follow-up is needed to evaluate durability and everyday use patterns, so that 3D printing becomes a reliable clinical manufacturing approach.

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