

REVIEW ARTICLE

A multidisciplinary review on footwear 3D printing: From biomechanics to therapeutics

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Abstract

Advancements in three-dimensional (3D) printing have expanded design freedom across various fields, including footwear. Driven by recent progress in biomechanics, footwear has increasingly adopted complex structural designs to meet diverse functional demands, ranging from personal activity to competitive athletics and medical rehabilitation. Accordingly, the role of 3D printing in footwear development has become increasingly significant. This review categorizes the functions of footwear into protection, performance enhancement, and therapeutic applications, and systematically explores the impact of 3D printing on each of these primary functions. 3D printing technology enables the fabrication of complex but mechanically efficient structures, while the 3D scanning method facilitates the application of optimal, personalized designs tailored to individual biomechanics, which significantly impact all three functional areas of footwear. Such design advantages offered by 3D printing have been demonstrated across various fields, with both commercial and academic examples presented to support these findings. This review highlights interdisciplinary insights from biomechanics, ergonomics, and clinical studies to discuss the current status, limitations, and future potential of 3D-printed footwear. We conclude that continuous advancements in design methodology, material science, and printing technology will accelerate the adoption of 3D printing in next-generation footwear.

Keywords: 3D printing; 3D printed shoes; Footwear; Foot protection; Running efficiency; Foot orthotics

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1. Introduction

Footwear is an essential component of daily life, playing a crucial role in various physical activities. Traditionally, footwear has been designed to protect the foot from

external hazards by providing structural support and impact absorption, thereby minimizing the risk of injuries during movement. This protective function is a fundamental aspect of conventional shoes and also an essential factor in orthotic devices, which assist individuals with specific medical conditions. However, modern footwear designs have advanced beyond basic protective functions, incorporating advanced features such as athletic performance enhancement and even therapeutic approaches.¹ As such, footwear has significantly expanded its application areas from everyday life to specialized fields, ranging from high-performance sports equipment to medical rehabilitation tools. As the functions of footwear have evolved, footwear designs have become increasingly complex to meet diverse needs of users, prompting the incorporation of innovative manufacturing techniques. In recent years, additive manufacturing, commonly known as three-dimensional (3D) printing technology, has emerged as a transformative approach in footwear manufacturing, enabling unprecedented design freedom and facilitating intricate structural designs to fulfill advanced functional requirements.

To fully exploit the potential of 3D printed footwear, it is essential to first understand the basic and advanced functions that modern footwear can offer. Footwear serves three primary functions: foot protection, performance enhancement, and therapeutic application. First, foot protection has always been a fundamental function of footwear, not only shielding the foot from external impacts but also preventing foot disorders caused by excessive strain and repetitive motion. Footwear helps alleviate fatigue during standing,²⁻⁴ enhances stability during walking,^{1,5-7} and ultimately reduces injury risk and improves comfort during full gait cycle. The second footwear function is performance enhancement. Key factors that influence gait performance include shoe weight,⁸⁻¹⁰ compression elasticity,^{11,12} longitudinal bending stiffness,¹³⁻¹⁷ and proper supporting.^{18,19} These factors can influence athletic performance by improving joint motion control, optimizing load distribution, and providing enhanced cushioning and support²⁰ for various physical activities. Lastly, the use of footwear as therapeutic aids is on the rise. Orthotic footwear is widely used for medical use. It can be categorized as foot orthosis, ankle-foot orthosis, insoles, or other shoe modifications. These orthoses have been used in the treatment of various adverse foot conditions, including flat feet,²¹⁻²⁶ plantar fasciitis,²⁷⁻³¹ diabetic foot,³²⁻³⁸ and even above-foot disease like knee osteoarthritis.³⁹⁻⁴² By modifying pressure distribution on the feet and improving the movement of the ankle and foot unit, orthosis can reduce pain and enhance physical function. As footwear continues to evolve its functions, there is a growing

interest in footwear design for improved functionality or personal customization. However, conventional footwear manufacturing relies on mass production techniques such as molding or casting, restricting the ability to create highly customized footwear tailored to unique foot structures and biomechanical needs of individual. This limitation on design freedom drives the demand for innovative manufacturing technologies, such as 3D printing.

3D printing offers unique advantages over traditional manufacturing methods. 3D printing enables direct fabrication of computer-aided design (CAD) into physical objects through layer-by-layer manner, allowing facile fabrication of complex structures. As the demand for diverse functions continues to grow, design of footwear has become increasingly complex. Therefore, manufacturing industry has revolutionized its production process by embracing 3D printing technology. This shift allows footwear manufacturing to overcome the limitations of traditional manufacturing methods and achieve unparalleled range of design options, opening a new pathway to the production of footwear with intricate but highly functional designs. The ability to design complex structures through 3D printing has contributed to improved foot protection, enhanced gait performance, and patient-specific therapeutic treatment, by incorporating features such as enhanced cushioning,⁴³ adaptive support,^{25,44-46} and customized fit^{31,47-49} that were previously unattainable with conventional manufacturing methods. Furthermore, employment of 3D scanning technology simplifies the customization process by rapid measurement and detailed feature capture, thereby facilitating the production of personalized footwear,^{36,44,47,50-52} as shown in [Figure 1](#).

Many recent publications have demonstrated the effectiveness of 3D printing in footwear manufacturing by highlighting its capability to create complex geometries and facilitate personalized design. Despite such advances, most 3D-printed footwear designs are still based on traditional design principles merely replicating conventional footwear structures, thus limiting the full potential of additive manufacturing. Therefore, rather than merely applying 3D printing to existing footwear designs, there is a growing demand for new design strategies that can fully utilize the capabilities of 3D printing for next-generation footwear. Given the multifaceted aspects of footwear functions, this review aims to achieve this goal by providing insights into footwear design from an interdisciplinary perspective, incorporating ergonomic, biomechanical, and therapeutic considerations. Then, we discuss various design advantages and unique characteristics of additive manufacturing, highlighting the strength of 3D printing

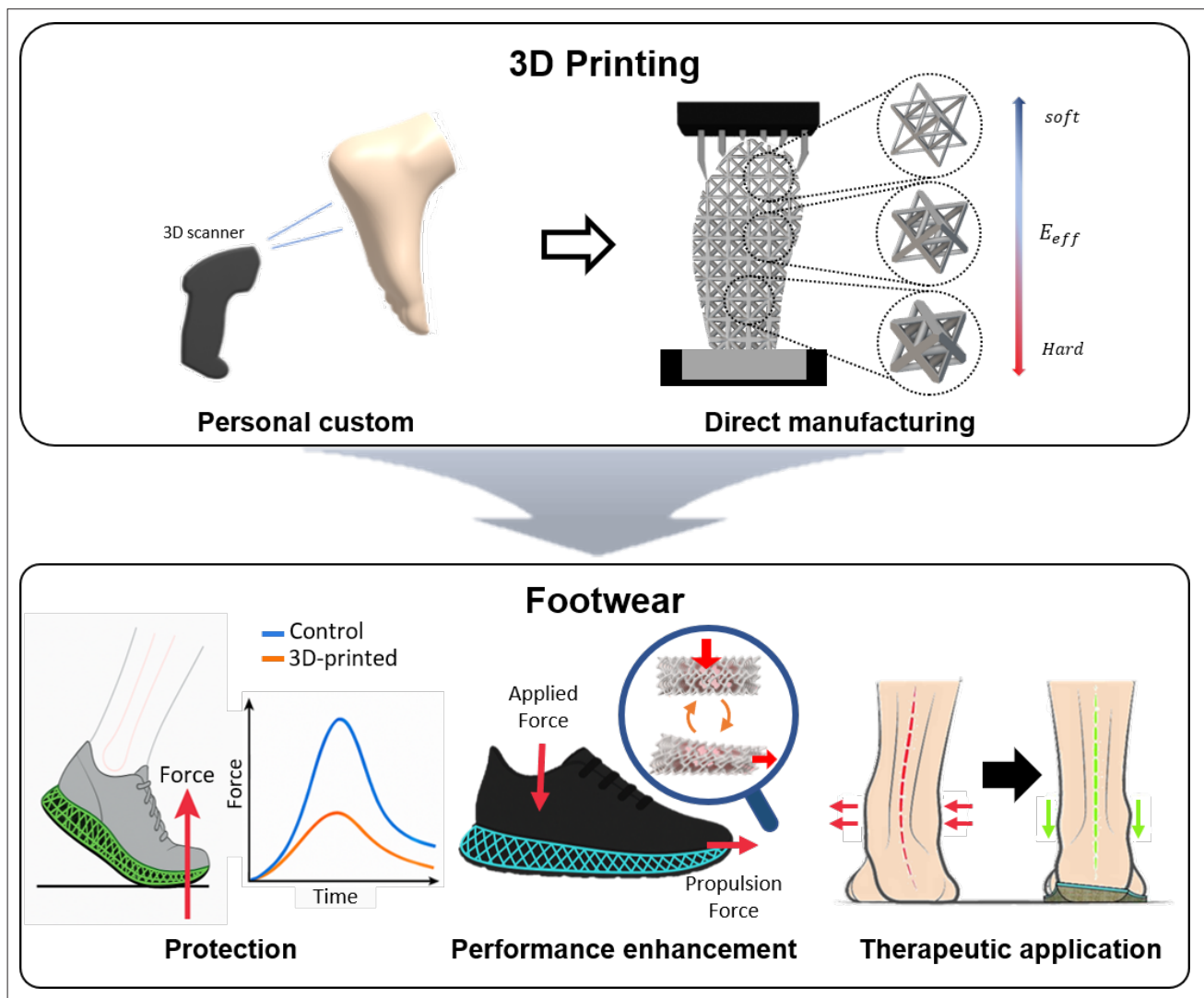


Figure 1. Overview of footwear, orthoses, and 3D printing

as an emerging manufacturing technology for footwear. Finally, we briefly address current limitations and future potential of 3D-printed footwear, suggesting diverse research directions for further exploration of additive manufacturing in footwear design.

2. Consideration of footwear function

Traditional footwear typically consists of two major components: the upper and the sole, with the sole further subdivided into three parts: insole, midsole, and outsole. While the upper plays a crucial role in fit and comfort, most footwear research has focused on the sole, which interacts with the plantar surface of the foot and the ground.^{6,53} This section examines three key functional aspects to consider when manufacturing 3D-printed

footwear. First, we discuss ‘protection’, the most basic and traditional function of footwear, exploring how 3D-printed midsole materials and outsole thickness can contribute to foot safety and injury prevention. Next, we focus on ‘performance enhancement’, a core element in modern footwear industry, analyzing how 3D-printed sole properties and contours can enhance energy return and mechanical efficiency during athletic activities. Finally, we examine ‘clinical application’ investigating how 3D-printed insoles and orthosis, with their capacity for precise geometric customization, can address specific pathologies and biomechanical abnormalities. Through these three perspectives, we aim to provide a comprehensive understanding of the current state and future possibilities of 3D-printed footwear technology.

2.1. Protection

Historically serving as physical safeguard for the feet, footwear has evolved from primitive coverings to technologically advanced systems that protect foot biomechanics.³⁴ During gait, the foot performs three mechanical functions: the heel absorbs shock at initial contact, the midfoot arch stabilizes body weight (BW) transfer from heel to toe, and the forefoot acts as a lever arm for effective propulsion.^{55–57} Footwear has to support these functions to reduce injury risks and provide comfort.⁵⁸ This section categorizes the protective functions into three aspects: impact distribution and absorption, structural support and stability, and individual fit and customization. It reviews representative applications in each domain (Figure 2), with particular focus on how these principles can be applied and extended through 3D printing technologies.

2.1.1 Impact distribution and absorption

Footwear mitigates mechanical loading by redistributing impact forces across the foot. While walking and standing generate relatively low ground reaction forces (GRFs) (approximately 1.0–1.2 BW), long exposure can cause fatigue, swelling, low-back pain, and foot problems like plantar fasciitis and blisters.² Prolonged stress can impair balance due to reduced sensory feedback and muscle fatigue.^{3,4} Footwear with effective cushioning, thicker soles, and rocker profiles (Figure 2A) helps to alleviate localized pressure and fatigue.^{2,43,59–62}

In running, GRFs reach 2–3 BW, potentially elevating the risk for running-related injuries.^{1,5–7} The midsole technologies target shock attenuation, with maximalist (or heavily cushioned) footwears exemplifying the approach through increased stack height (Figure 2B; Hoka One One Clifton 2) and compliant foams (Figure 2C).^{12,53,63,64} However, evidence supporting these assumptions remains inconclusive. Some studies question whether cushioning effectively reduces impact loading or injury risk, and suggest that excessive cushioning may even reduce proprioceptive feedback, potentially increasing injury risk in other ways.^{65,66}

Optimal cushioning is highly individual-dependent, influenced by body mass index, foot morphology, and running patterns. Recent trends emphasize personalized cushioning through strategic midsole tuning rather than a one-size-fits-all approach.^{1,67} In this context, lattice structures in shoe soles using 3D printing have emerged as a promising solution. Their geometry can be precisely engineered to manipulate stiffness and pressure distribution under dynamic loading^{68–71} (Figure 2D). Moreover, 3D-printed design offers significantly

greater room in structural configuration than traditional dual-density footwear, which typically relies on layering different materials.⁷² Advanced 3D-printed geometries—such as variable-density lattices (Figure 2D), directional spring structures (Figure 2E), honeycomb configurations (Figure 2F), and spiral supports (Figure 2G)—enable modulation of cushioning and plantar pressure redistribution within a single continuous structure.^{72–74}

In summary, impact protection in footwear design should be viewed not only as a function of material properties but also as a matter of geometric customization. 3D printing enables region-specific modulation of compliance and damping, allowing designers to address diverse biomechanical demands through individualized structural solutions. Through 3D printing, region-specific compliance and force attenuation can be finely modulated to address the biomechanical needs of diverse users.

2.1.2 Structural support and stability

Foot stability and injury prevention are influenced by midsole and insole geometry, outsole traction, and upper fit. As soles became thicker and more compliant in the 1970s, stability trade-offs emerged.⁵³ Thicker midsoles raise the center of mass and increase leverage at the subtalar joint, reducing lateral ankle stability.⁶⁷ In response to these stability concerns, footwear developers in the 1990s introduced various motion-control features—such as medial posts, heel flares, firm heel counters—to mitigate excessive rearfoot motion (Figure 2H).^{1,5,6,53,54,58,75} Firm heel counters (Figure 2H) function to cradle the rearfoot and limit rearfoot eversion, which is particularly critical for individuals with excessive pronation or medial instability. Footwear have been reported to be effective in pathologic conditions such as flexible flatfoot, where controlling excessive pronation and medial collapse is crucial. However, evidence on their efficacy in injury prevention remains inconclusive under physiologic conditions, due to individual differences in foot structure, gait patterns, and biomechanics.^{6,65}

Outsole traction is a critical component of stability; insufficient grip may lead to slipping, while excessive grip can result in torque-related injuries such as tears in anterior cruciate ligament and ankle strains,⁷⁶ highlighting the need for an optimal balance. Tread patterns (Figure 2I) vary in depth and type, with deeper patterned treads providing greater traction for activities requiring higher grip such as trail running.^{54,77,78} Optimal outsole design must balance slip resistance and safe rotational freedom for different sports and surfaces.

The shoe's upper (the enclosing material and lacing system) serves as the interface between foot and shoe,

playing a vital role in stability, fit and breathability. Inadequate toe box fit can lead to friction injuries (e.g., blisters, bunions), while excessive looseness compromises stability.^{7,63,79} Modern designs use adaptive uppers (e.g., BOA® lacing (Figure 2J)), knit fabrics (Figure 2K), overlays) to enhance fit while maintaining flexibility.^{80–83} Although research on upper fit’s direct impact on injury rates remains limited, it is widely acknowledged as essential for structural support, particularly in sports involving rapid directional changes.^{63,84}

From a 3D printing perspective, these findings highlight opportunities for integrating heterogeneous stiffness profiles and upper-midsole interactions within

a single print. Customized heel counters, arch bridges, or lateral supports could be embedded directly into the midsole geometry, enabling targeted reinforcement without compromising comfort. Such designs open the door to patient-specific pronation control and stability optimization.

2.1.3. Individual fit and customization, and smart footwear

As discussed in Sections 2.1.1 and 2.1.2, no universal “ideal shoe” exists for preventing injuries, as effectiveness varies across individuals based on foot shape, biomechanics, past injury history, and activity patterns.^{6,7,20,65,79,85–93} Instead of

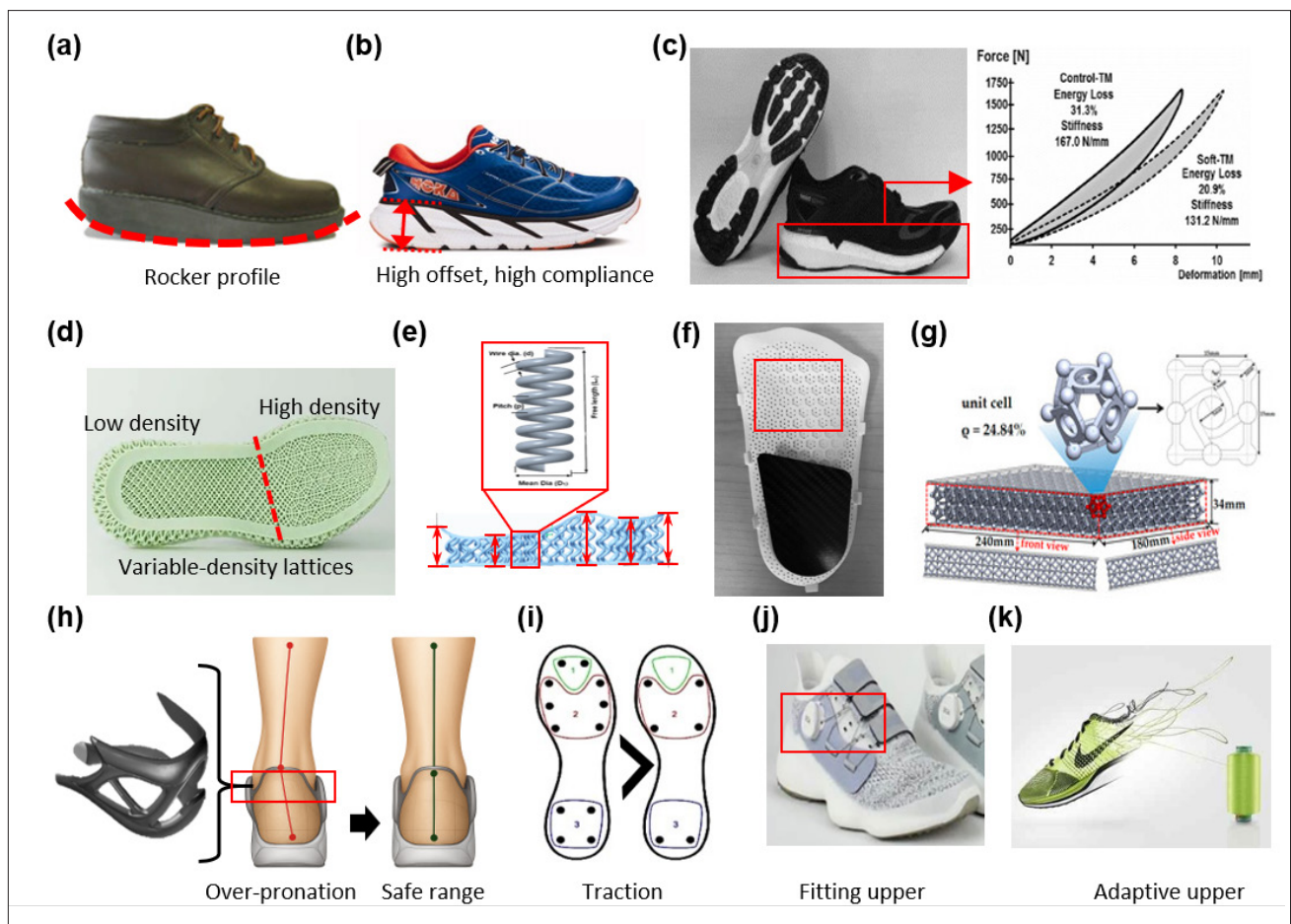


Figure 2. Representative design features and technologies for protective functions in footwear. (A) Rocker-profiled sole forward roll-over. Adapted with permission from ref.² Copyright © 2016 Elsevier. (B) Maximalist running shoe with enhanced cushioning. Adapted with permission from ref.⁶⁴ Copyright © 2021 Taylor & Francis. (C) Running shoe providing foam cushioning. Adapted with permission from ref.¹² Copyright © 2014 Taylor & Francis. (D) 3D-printed lattice with region-specific compliance. Adapted from ref.⁷¹ (E) Helical lattice for zonal stiffness variation. Adapted with permission from ref.⁷² Copyright © 2020 Springer Nature. (F) Honeycomb unit-cell for midsole lattices. Adapted with permission from ref.⁷³ Copyright © 2021 Elsevier. (G) Spiral topology of midsole lattices with directional shock absorption. Reproduced from ref.⁷⁴ (H) CAD-modeled heel counter for rearfoot stability. Adapted with permission from ref.⁷⁵ Copyright © 2009 Taylor & Francis. (I) Outsole patterns for traction. Adapted from ref.⁷⁸ (J) BOA® lacing system for adjustable foot lockdown. Adapted with permission from ref.⁸² Copyright © 2023 Taylor & Francis. (K) Stretchable Flyknit upper. Reproduced from ref.⁸³ Abbreviation: CAD, computer-aided design.

prescribing a single correct shoe type, the focus has shifted to modular and customizable designs that allow for fine-tuned adjustments. 3D printing plays a key role in this shift, offering capabilities for individualized fabrication of midsoles, insoles, and uppers tailored to specific anatomical and biomechanical profiles.^{69,94–96}

Recent advances have extended this customization potential to smart footwear by enabling the direct integration of embedded sensors in 3D-printed footwear. For example, one study presented a sensor-integrated insole that facilitates iterative redesign and fabrication by capturing gait and pressure data to inform personal biomechanical data.⁹⁷ Another study demonstrated real-time pressure sensing and wireless data streaming during walking, suggesting the potential of responsive, sensor-integrated footwear in real-world settings.⁹⁸ Currently, sensor-integrated footwear systems are limited to relatively simple measurements compared to conventional sensor platforms. However, with advances in 3D printing and sensor technologies, more complex sensing functions—such as advanced gait analysis and real-time impact feedback—may become achievable. These capabilities could be further enhanced through the future integration of AI-driven sensing and data interpretation frameworks. If such advancements are realized, sensor-integrated footwear may eventually replace traditional foot pressure sensors and significantly enhance therapeutic applications by enabling more responsive and adaptive interventions. Furthermore, the ability to directly acquire digitized sensor data from the footwear itself offers new opportunities for producing improved customized insoles.⁹⁷ If future research enables the effective coupling of this sensor data with footwear design, potentially through AI-driven methods, it could accelerate the development of next-generation smart footwear tailored to individual biomechanical requirements.

2.2. Performance enhancement

Footwear contributes not only to protecting lower extremities but also to enhancing biomechanical efficiency. Gait motion can be categorized into walking and running, but biomechanical performance is particularly relevant to running and high-intensity movements.^{18,19,99} Therefore, this section will focus on various footwear designs for improving running performance. Performance-related benefits of footwear include reducing metabolic cost, improving running economy (RE), and optimizing force transmission.^{100,101} Among these, RE is one of the most commonly used indicators for comparing different footwear properties.^{102,103} RE refers to the amount of oxygen consumption at a given submaximal speed, and better RE indicates a lower metabolic cost for the same pace or

workload, allowing the runner to go faster or farther for the same physiological capacity.¹⁰⁴ Footwear contributes to performance through multiple mechanisms. In this section, we reorganize previous categories into three key factors: mass and propulsion efficiency, push-off mechanics and energy efficiency, and fit and force transmission. Then, we discuss how each factor can be leveraged through 3D printing technologies (Figure 3).

2.2.1. Mass and propulsion efficiency

Shoe mass plays a critical role in performance, particularly during cyclic lower-limb movements like running. Research suggests that reducing shoe mass by 100 g leads to approximately 1% improvement in RE.⁸ This effect is attributed to decreased moment of inertia, lowering leg swing cost, which can account for up to 20% of the total running energy expenditure.^{9,10} Consequently, modern racing shoes prioritize minimal weight to enhance efficiency.

3D printing enables targeted ultra-lightweight through process-level innovation and structural design. For instance, On Running's Cloudboom Strike LS applies LightSpray™ technology (Figure 3A)—a one-step, robotic spray-deposition method that forms a seamless 30 g upper without stitching or adhesives.⁹⁶ Additionally, engineered hollow-core midsoles, such as in Under Armour's Architech shoe or On Running's Cloudmonster Hyper (Figure 3B) demonstrate how lightweight design can preserve cushioning through internal voids.^{105,106}

2.2.2. Push-off mechanics and energy efficiency

Midsole thickness, elasticity, and material composition significantly influence performance.¹¹ Responsive midsoles, made from elastic materials, such as ethylene-vinyl acetate (EVA) foam or specialized cushioning technologies, provide energy return for efficient push-off.¹² The curves in Figure 3C illustrate how midsole materials differ in compliance (amount of deformation, upper trace in each curve) and resilience (efficiency of energy return, lower trace¹⁰⁴). The area between the loading and unloading curves indicates energy loss, while the area under the unloading curve reflects the elastic energy returned. High-rebound foams, such as thermoplastic polyurethane (TPU) (adidas Boost™) and Pebax® foams (Figure 3C), introduced in the 2010s, offered greater energy return and lower density than classic EVA, contributing to about 1% RE improvement.^{104,107} Thicker foam also increases effective leg length and stride length, enhancing RE.⁹⁹

The incorporation of carbon fiber plates in the midsole increases longitudinal bending stiffness (Figure 3D)^{13,14,104} It can enhance push-off efficiency by limiting metatarsal-phalangeal joint movement and increasing the mechanical

advantage of the GRF lever arm.^{14–16} This is beneficial because less bending at the toes means less energy lost to stretching and recoiling those joints.^{14,15} Among other factors, increasing longitudinal bending stiffness is evaluated as one of the most powerful factors that improves RE.^{14,100,101} The introduction of super shoes in 2017, combining ultralight Pebax® foam and carbon-fiber plates, reduced the energetic cost of running by 4%, translating to 2–4% faster race times.^{14,16,101} However, optimal stiffness varies across individual’s characteristics and running speed, and excessive stiffness can be counterproductive (Figure 3D).^{13,14,17,108}

3D printing offers a platform for precise control over energy return and bending behavior through geometric customization. Previously discussed lattice and variable-

stiffness designs (Figure 2D–G) can be engineered within a single midsole to meet individualized performance needs. Furthermore, the technology allows designers to engineer lattice structures that can be deformed to redirect vertical impact forces into forward-propulsive components.^{109,110} For instance, Adidas’ 4DFWD’s directional lattice structures (Figure 3E⁶⁹) demonstrate how 3D-printed geometry can actively redirect forces to improve propulsive efficiency.

2.2.3. Fit and force transmission

Footwear fit and traction directly influence biomechanical efficiency by affecting the coupling between the foot and the ground. A secure, personalized fit minimizes internal foot-shoe motion and enhances comfort, thereby reducing energy wasted on compensatory muscle activation.^{18,19}

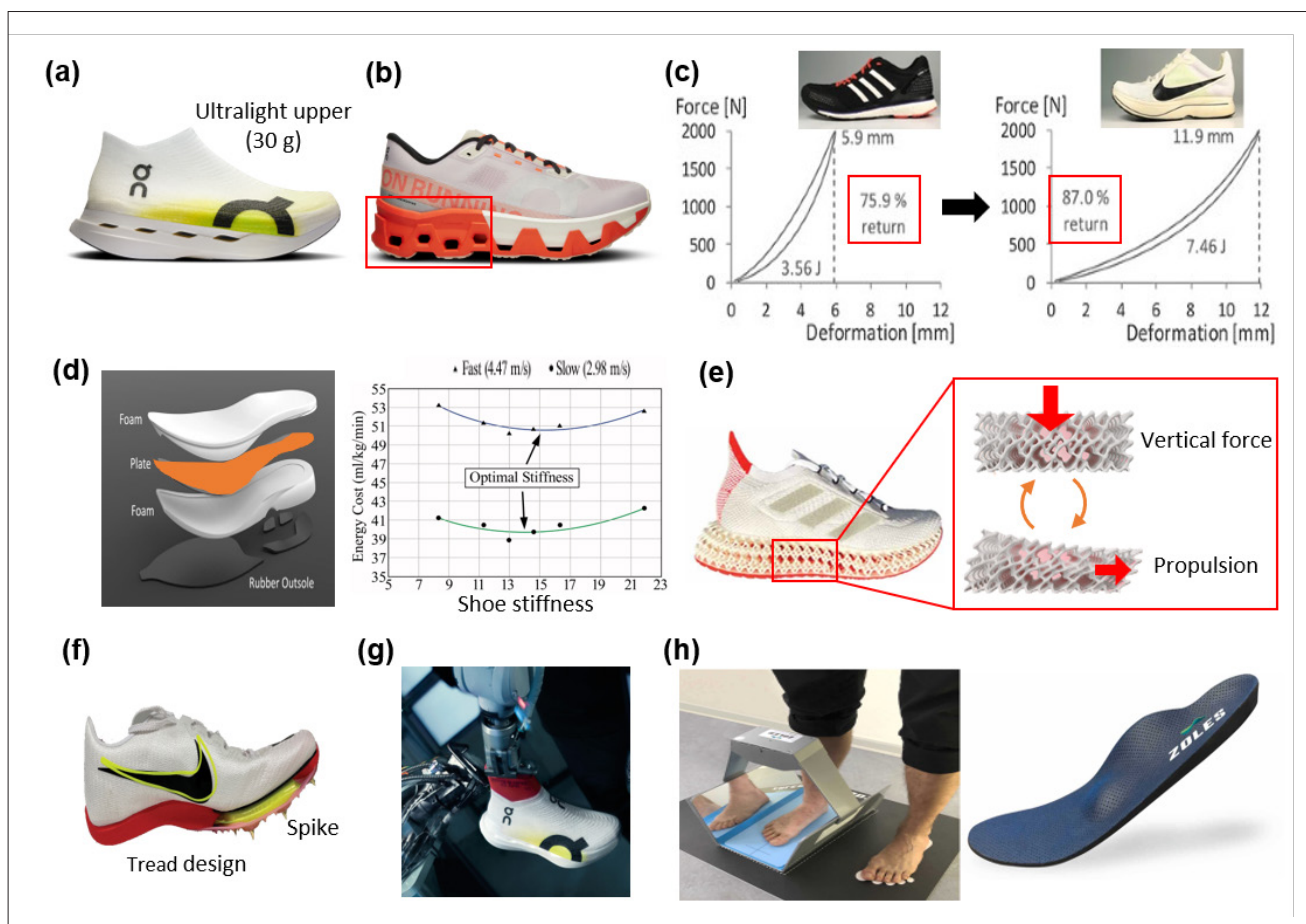


Figure 3. Representative footwear technologies and 3D printing applications for performance enhancement. (A) Light footwear with ultralight upper. Reproduced with permission from ref.⁹⁶ Copyright © 2025 On AG. (B) Light footwear with hollow midsole lattice. Reproduced with permission from ref.¹⁰⁶ Copyright © 2025 On AG. (C) Mechanical comparison of low- and high-rebound midsoles. Adapted from ref.¹⁰⁴ (D) Longitudinal bending stiffness: carbon-fiber plate schematic (left; adapted from ref.¹⁰⁴) and optimal stiffness curve showing minimized oxygen cost (right; reproduced with permission from ref.¹⁰⁸ Copyright © 2020 Taylor & Francis). (E) Anisotropic midsole lattice promoting forward shear deformation. Adapted with permission from ref.⁶⁹ Copyright © 2022 Taylor & Francis. (F) Track spike with integrated carbon plate for propulsion. Adapted with permission from ref.⁹⁹ Copyright © 2022 Taylor & Francis. (G) Spray deposition technology for ultralight, form-fitting uppers. Reproduced with permission from ref.⁹⁶ Copyright © 2025 On AG. (H) Personalized 3D-printed insoles based on foot scans. Reproduced from ref.¹¹³

Likewise, outsole traction governs how effectively applied force is transmitted into forward motion. Both aspects are crucial for improving RE, especially under high-intensity or multi-directional loading.

Upper materials and systems have evolved to balance lockdown and compliance. Technologies such as BOA® systems (Figure 2J) and knit meshes (Figure 2K) conform to individual foot morphology while maintaining structural security.^{82,83} Research demonstrated that runners consumed 0.7% less oxygen when wearing the shoes, which they rated as the most comfortable and well-fitted,¹⁰⁷ indicating that perceived comfort aligns with reduced metabolic cost.

Outsole compounds and tread geometries further affect energy efficiency. Insufficient grip can lead to compensatory muscle activation and increased oxygen cost, while excessive grip may increase torque-related injuries.⁹⁹ Advanced footwear technologies, including specialized 'super spikes (Figure 3F)', now feature lightweight carbon rubber, tuned spike placement, and tread patterns to improve grip on track surfaces,¹¹¹ contributing to recent record-breaking track performances.⁹⁹

3D printing expands the design space across these domains by enabling precise control over geometry and material properties.¹⁴ Technologies such as Nike's Flyprint™ and On's LightSpray™ (Figure 3G) exemplify how 3D printing enables ultralight, form-fitting uppers with seamless support and adaptive lockdown.^{81,96,112} These designs eliminate conventional stitching and lacing, offering precision fit and minimized distraction—especially beneficial under race-day conditions.^{110,112} Personalized insoles fabricated from foot scans and plantar pressure data (Figure 3H¹¹³), as demonstrated in both research workflows¹¹³ and commercial services like those offered by ASICS.¹¹⁴ Such designs can contribute to improving perceived comfort and gait stability, especially in individuals with foot deformities like flat feet or arthritis.^{24,25} Additionally, outsole traction patterns can be directionally optimized through additive manufacturing, which allows data-driven personalization of outsole geometry based on gait asymmetries or sport-specific ground interactions. Together, these advances illustrate how 3D printing supports integrated, performance-driven customization across upper, midsole, insole, and outsole components.

2.3. Clinical applications

Specialized therapeutic footwear and orthotic interventions play a critical role in managing various foot disorders by redistributing plantar pressure, reducing impact force, and correcting deformities. Clinical applications represent one of the earliest domains where customized

footwear approaches were introduced, with skilled orthopedic shoemakers crafting personalized solutions for individuals with specific needs. The most representative foot disorders treated by footwear modification are flat feet, plantar fasciitis, and diabetic foot. Additionally, footwear modifications are also prescribed for conditions affecting areas above the foot, such as knee osteoarthritis and leg length discrepancy. In this section, we review both foot disorders and above-foot disorders, considering the potential for 3D printing technology to address these clinical needs (Figure 4).

2.3.1. Clinical applications for foot disorders

Flat feet are primarily caused by ligamentous laxity or dysfunction of the tibialis posterior muscle, leading to foot deformities such as a lowered medial longitudinal arch, rearfoot eversion, and forefoot abduction.^{21,22} Although various insoles are used to correct flat feet, no standardized form exists. The most representative designs involve inverting the rearfoot, providing medial arch support using fill or flange, and a forefoot post (Figure 4A)^{23,26,28,115} These modifications are designed to control foot pronation, reduce GRF, and redistribute midfoot pressure.²⁴ The evidence supporting insole effectiveness for flat feet remains limited. A systematic review of 13 studies found moderate to good evidence for improvements in physical function, but insufficient evidence for reductions in pain, foot kinetics, and rearfoot kinematics.²³ This gap stems primarily from the scarcity of well-designed randomized controlled trials examining specific design elements and their correlation with clinical outcomes. Conducting such trials is particularly challenging due to differences in foot structure between individuals, making it difficult to standardize treatment protocols and assess outcomes consistently.

Plantar fasciitis is characterized as chronic injury at the origin of the plantar fascia, which commonly manifests as a painful heel. The primary pathogenesis involves cumulative strain at the plantar fascia insertion, exacerbated by various mechanical factors including flat feet, high-arched feet, reduced ankle dorsiflexion range of motion, and deficits in ankle plantar flexor or toe flexor strength.²⁷ The most commonly studied orthotic device for the treatment of plantar fasciitis is the heel pad or cup, which can be made by either of silicone, nylon, rubber, or polypropylene (Figure 4B).^{29,30} These are frequently prescribed in combination with foot orthoses that support the medial longitudinal arch. The main purpose is to redistribute plantar pressure to reduce pressure beneath the painful heel and enhance the mechanical efficacy of plantar fascia.^{27,31}

Diabetic foot, affecting approximately 15% of the diabetic population, is a common complication primarily caused by peripheral neuropathy that impairs the feet’s sensory, motor, and autonomic nerve functions.³³ Sensory neuropathy results in loss of protective sensation, motor neuropathy leads to muscle atrophy and foot deformities, and autonomic neuropathy leads to dry skin and altered microcirculation. Excessive foot pressure due to limited joint mobility and deformities further increases the risk of tissue breakdown and ulcers.¹¹⁶

Orthotic interventions for diabetic foot management can be broadly classified into preventive and therapeutic applications. Preventively, customized footwear and inserts are essential to protect patients with reduced sensation from unnoticed injuries and excessive pressure.³³

Therapeutically, strategies vary according to clinical stage. During the early stage of diabetic foot management, movement is typically limited to prevent weight bearing on the injured area. However, when mobility is necessary, assistive devices such as walker boots or customized ankle-foot orthoses (Figure 4C³⁸) can be utilized. After the wound has been treated, therapeutic footwear, including in-depth shoes with accommodative inserts or triple-layer molded orthoses are commonly recommended for ongoing pressure management,³⁴ often with external shoe modifications such as rocker soles.³⁵ Despite strong clinical recommendations, current evidence supporting their efficacy remains limited,³⁷ highlighting the need for more rigorous clinical research. This challenge is further compounded by the considerable variability in

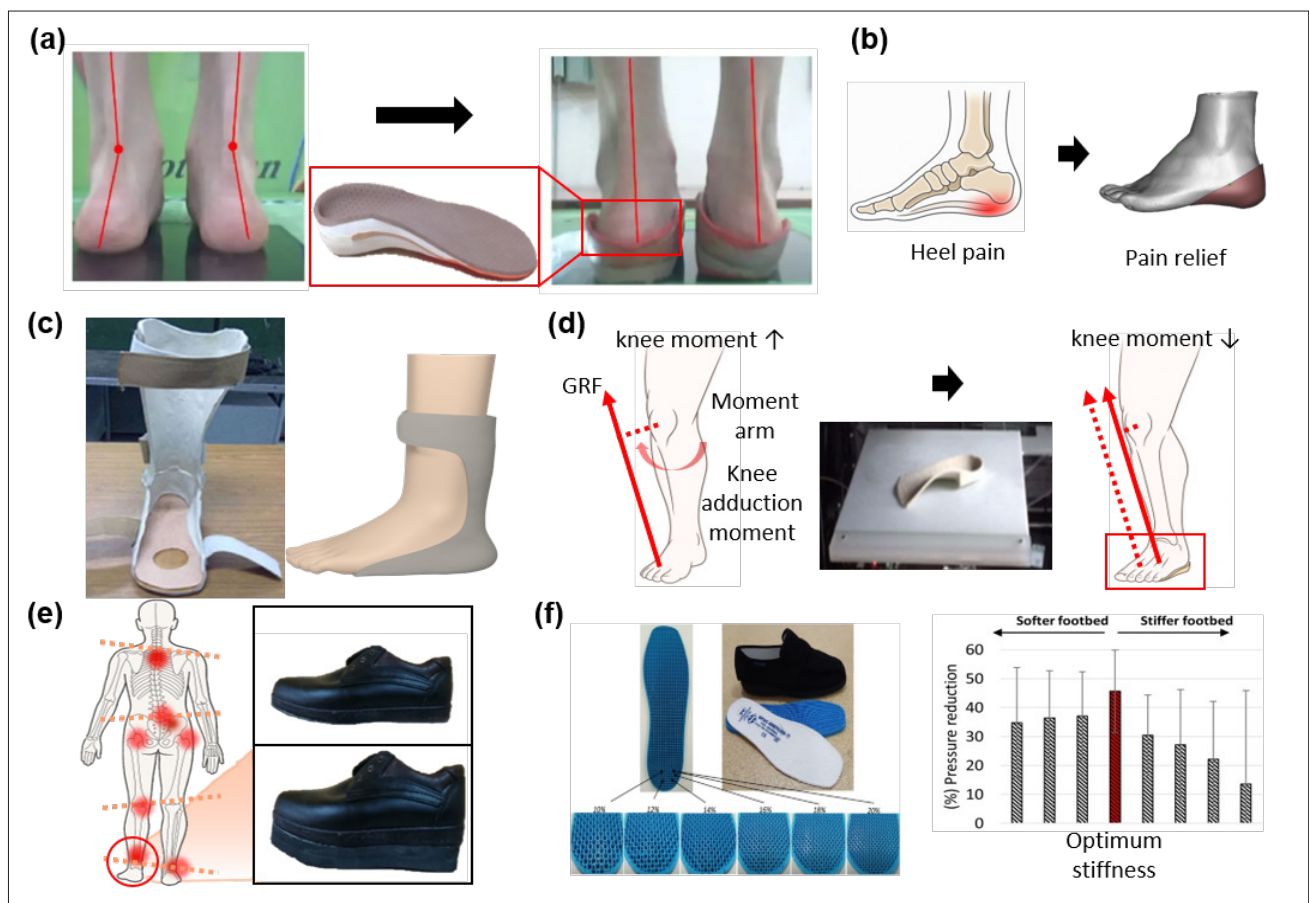


Figure 4. Clinical applications of footwear and orthotic devices enabled by 3D printing. (A) 3D-printed insoles for rearfoot inversion and medial arch support in flat feet. Adapted with permission from ref.²⁶ Copyright © 2020 Elsevier and ref.¹¹⁵ Copyright © 2022 Springer Nature. (B) Heel cup to relieve heel strain and redistributes pressure in plantar fasciitis. Adapted from ref.²⁹ (C) Ankle-foot orthoses for pressure offloading in diabetic foot. Adapted with permission from ref.³⁸ Copyright © 2014 Diabetes Technology Society. (D) A 3D-printed lateral wedge insole to reduce knee adduction moment in knee osteoarthritis. Adapted with permission from ref.⁴¹ Copyright © IMechE 2017. (E) Insole and outsole modifications for postural alignment in scoliosis and leg length discrepancy. Adapted with permission from ref.¹²⁰ Copyright © 2022 Elsevier. (F) A 3D-printed porous insole with region-specific stiffness for plantar pressure reduction (left) and optimal stiffness (right). Reproduced with permission from ref.¹²¹ Copyright © 2020 Elsevier. Abbreviation: GRF, ground reaction force.

lesion location and severity among patients, necessitating personalized assistive device match with individual needs. 3D printing technology is able to address this issue by enabling efficient customization of orthoses and footwear, providing targeted pressure relief and structural support tailored to each patient's specific condition.

2.3.2. Clinical applications for above-foot disorders

Shoe modifications can be used to treat not only foot disorders but also disorders occurring above the foot, such as medial knee osteoarthritis, scoliosis, and leg length discrepancy. In knee osteoarthritis, the medial compartment is more preferentially degenerated than the lateral compartment, causing the malalignment of knee joint, or genu varum (bow-legged deformity).⁴⁰ Lateral wedge insoles (Figure 4D) are prescribed to shift the center of pressure laterally, thereby reducing the knee adduction moment.^{40-42,117} Meta-analyses have confirmed their effectiveness in pain reduction,⁴⁰ with significant reductions in both external knee adduction moment and knee adduction angular impulse in individuals with this condition.³⁹

For patients with scoliosis and leg length discrepancy, various shoe modifications offer therapeutic benefits. These include heel pads, outsole modifications, and heel lift insoles (Figure 4E). Such interventions aim to improve spinal deformity, enhance static balance, and compensate for leg length discrepancy and its associated biomechanical consequences.¹¹⁸⁻¹²⁰

2.3.3. Role of 3D printing in clinical applications

In clinical footwear, patient-specific intervention is essential, and 3D printing offers key advantages over conventional methods by significantly reducing cost, weight, and production time. Using individual foot scans and plantar pressure maps, 3D printing allows for the fabrication of precision orthoses tailored to anatomical and functional needs. For example, insoles with graded stiffness or geometry-optimized arch supports have been shown to improve gait stability and comfort in patients with flat feet or arthritis (Figure 4A and B).^{24,26,30} In diabetic foot, 3D-printed ankle-foot orthoses and custom rocker soles can deliver targeted offloading, while also accommodating complex deformities that evolve over time (Figure 4C). Additionally, porous insoles manufactured via 3D printing have demonstrated effectiveness in redistributing plantar pressure by adjusting regional stiffness based on pressure data (Figure 4F).¹²¹ For above-foot disorders such as medial knee osteoarthritis, the ability to digitally model and print lateral wedge insoles or corrective lifts allows for better alignment control with reduced material bulk (Figure 4D).⁴¹ These attributes position

3D printing as a transformative tool in clinical footwear design, capable of delivering scalable, personalized, and evidence-informed interventions.

3. Integration of 3D printing technology into footwear manufacturing

The design and manufacturing of footwear have continuously evolved to meet the functional demands of protection, performance enhancement, and therapeutic application. Traditional footwear manufacturing has undergone significant transition, from craftsmanship-based manufacturing to mechanized mass-production. However, the reliance on molding and casting limits the design complexity of footwear, and multi-step assembly still requires human involvement. These constraints hinder the development of highly optimized footwear designs that could enhance biomechanical functionality.

Additive manufacturing, commonly known as 3D printing, has revolutionized the footwear industry by providing an unprecedented level of design freedom.^{122,123} Unlike conventional methods, 3D printing enables the direct fabrication of digitally modeled structures, which are too intricate to be manufactured using traditional techniques. This approach allows for the creation of highly optimized geometries to enhance performance by integrating metamaterial structures, gradient stiffness change, and adaptive cushioning.^{44,124} Avoiding the need for physical molds in the manufacturing process has also enabled rapid prototyping. This approach is particularly effective for personalized shoes, which traditionally require labor-intensive and time-consuming tasks due to customization process (Figure 5A).^{44,50} Customization plays a crucial role in protection and therapeutic applications, as footwear must accommodate unique foot structures and biomechanical needs to prevent injuries and support medical treatments. Several recent studies have explored the application of 3D printing and 3D scanning in accommodating these individual variables and developing customized footwear solutions to treat foot disorders (Figure 5B).^{36,44,47}

Beyond improvements in footwear functions, 3D printing also offers significant advantages in streamlining the manufacturing process and reducing production time, particularly for small-batch, customized production. While traditional manufacturing remains faster for mass production, 3D printing accelerates personalized product development by enabling direct fabrication from digital models, often informed by 3D scanning of user-specific anatomy data. In addition, the elimination of molds and tooling streamlines the prototyping process, allowing for faster transitions from design to physical

product. For example, it has been reported that the total product development cycle for footwear, including design, testing, and production, which typically takes 15–18 months in conventional manufacturing, was shortened by approximately 40% when 3D printing was employed.¹²⁵ These advantages have driven major footwear companies such as Adidas, New Balance, and Nike to form partnerships with 3D printing enterprises. As a result of these collaborations, several commercially available 3D-printed footwear models, such as Adidas' 4DFWD™ series and New Balance's TripleCell™, have been introduced to the market. This progress demonstrates the viability and potential of additive manufacturing and reflects the growing role of the technology in the footwear industry.

In this section, we provide comprehensive overview of the design advantages, fabrication method, and current applications of 3D-printed footwear.

3.1. Design advantages of 3D-printed footwear

3D printing provides significant design advantages, such as the freedom to fabricate complex geometries, precise structural control, and simplified manufacturing processes. Among these advantages, one notable approach is the monolithic design, which is created by directly fabricating footwear without the need for assembly between different materials. This approach eliminates seams, resulting in a more durable and sustainable product that avoids structural weaknesses typically associated with multi-material interfaces (Figure 5C).^{126,127} Therefore, footwear fabricated with a monolithic design provides enhanced foot protection by minimizing stress concentrations and reducing the likelihood of material failure under repetitive loading conditions. It has been especially beneficial for orthotic insoles, optimizing their production and long-term durability for clinical applications.^{46,48,49,128,129} Lastly, a simplified manufacturing process improves sustainability by reducing material waste and production time.

Mechanical metamaterials are one of the most representative structures that highlight the design advantages of 3D printing, which cannot be fabricated through traditional manufacturing methods. These complex artificial porous structures can enhance the performance efficiency of physical activities by leveraging their lightweight properties¹³⁰ and adaptive stiffness control.⁴⁴ Unlike traditional materials, which require material modifications to adjust stiffness, metamaterials enable precise stiffness control solely through structural design (Figure 5D).³⁴ This characteristic allows footwear to have variable stiffness options, making it an ideal candidate for both high-performance and therapeutic applications. For instance, sports footwear brands such as

Adidas and Carbon 3D, incorporate bow-tied shape lattice midsoles that convert vertical pressure into horizontal force to improve running performance.⁶⁹ Additionally, custom insoles with porous structure have been developed for diabetic foot treatment, aiming to prevent ulcers by reducing localized pressure points through gradient stiffness variation (Figure 5E).^{44,45}

The convergence of 3D printing and scanning technologies can significantly impact the design of personalized footwear. While 3D scanning-based personalized footwear serves various functions, it is particularly crucial in therapeutic applications. This approach digitalizes the orthosis manufacturing process for clinical applications, reducing production time and eliminating labor-intensive procedures which were conventionally performed exclusively by licensed orthotists.^{44,48,50} These conventional methods typically involve using foam impression boxes or plaster casting, where physical contact is unavoidable and may alter the natural posture of the foot. In contrast, 3D scanning offers a contactless and accurate measurement of anatomical details without distortion. Furthermore, acquired scan data can be customized through CAD modeling to optimize pressure distribution, arch support, and motion control (Figure 5F and G).^{29,46} This process enables precise customization and adaptation to the individual's specific requirements. For instance, direct scanning of the posterior ankle and legs is utilized in designing ankle-foot orthoses,^{50–52,129,131,132} and when direct foot scanning is challenging, scanning foam impression boxes serves as an effective alternative.^{25,44,47} Additionally, force plate measurements on plantar pressure distribution are often combined with 3D scanning data, to design orthotic insoles that provide optimal support and alleviate high pressure.^{25,46}

3.2. 3D printing methods and materials

Despite extensive research on 3D printing driven by its design advantages, the range of available materials remains limited. Within the realm of footwear production, elastomeric materials are conventionally used to manufacture the sole component because of their properties, such as shock absorption and enhanced user comfort. However, the range of elastomers available for 3D printing is relatively limited, compared to rigid materials. Various 3D printing techniques, such as fused deposition modeling (FDM), selective laser sintering (SLS), and vat polymerization, have been employed in footwear fabrication (Figure 6A).¹³³

FDM is one of the most commonly used 3D printing methods due to its cost-effectiveness and simplicity. In FDM, filament is melted and deposited through a nozzle onto a partially constructed 3D structure. TPU, polylactic

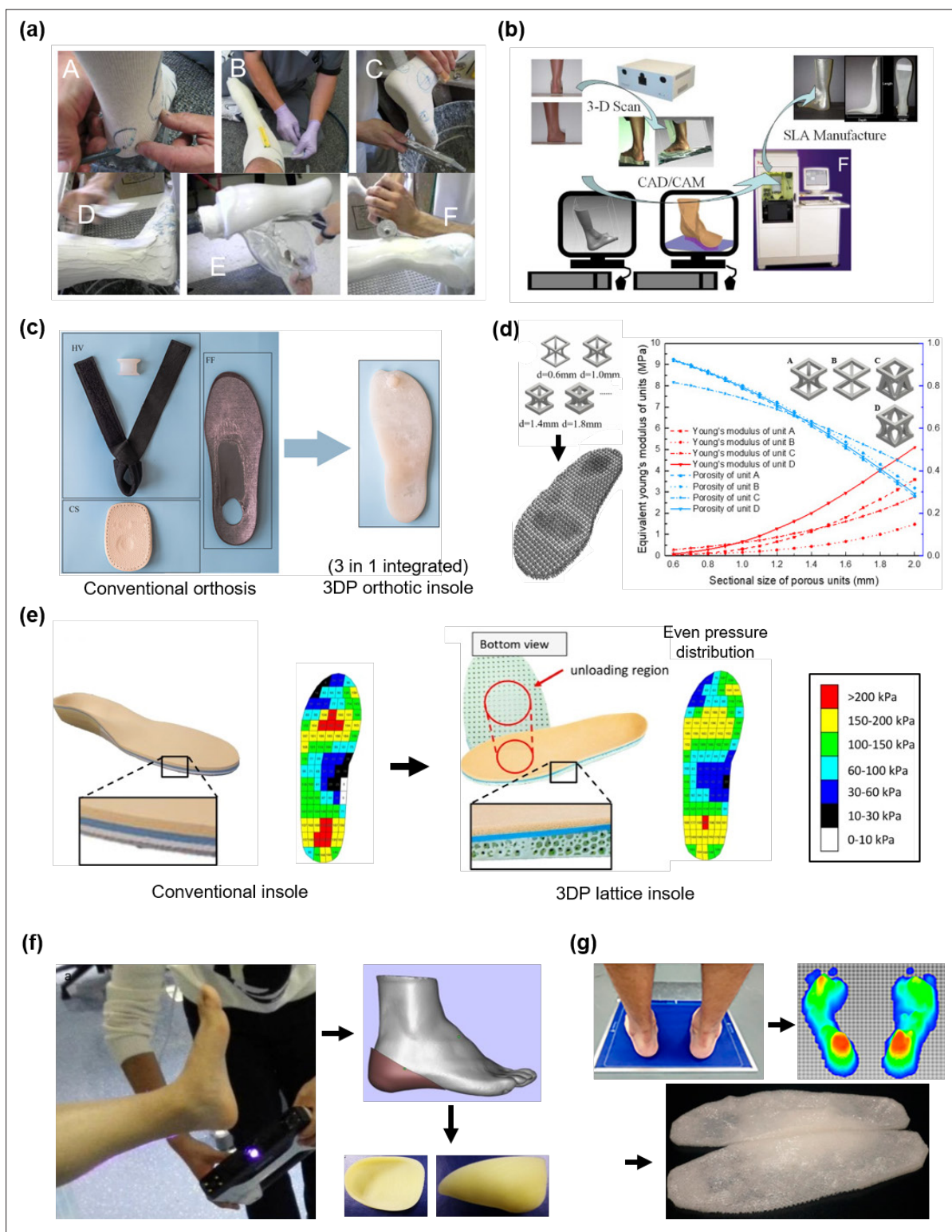


Figure 5. Design advantage of 3D-printed footwear. (A, B) Comparison of footwear manufacturing methods, and (C–G) design advantage. (A) Conventional orthosis manufacturing. Reproduced from ref.⁵⁰ (B) 3D-printed footwear manufacturing. Reproduced from ref.⁵⁰ (C) Monolithic design. Reproduced with permission from ref.¹²⁷ Copyright © IMechE 2021. (D, E) Insole with lattice structure. Adapted with permission from ref.³⁴ Copyright © 2019 Elsevier and ref.⁴⁴ Copyright © 2022 Elsevier. (F, G) 3D scanning and manufacturing. Adapted from refs.^{29,46} Abbreviations: 3DP, 3D-printed; CAD/CAM, computer-aided design/computer-aided manufacturing; SLA, stereolithography.

acid, and acrylonitrile butadiene styrene are generally used materials for fabricating orthoses (Figure 6B and C).^{25,46,122,123}

SLS is a technology that uses a high-power laser to selectively sinter powder particles into a solid object. Ankle-foot orthoses have been fabricated using SLS due to their complexity and cost-effectiveness (Figure 6D).^{51,131,134} In order to minimize energy dissipation during walking, ankle-foot orthoses are typically fabricated using materials like Nylon, which are rigid but offer limited flexibility. Foot orthoses printed by SLS with such materials have been validated through actual walking and mechanical failure tests (Figure 6E).^{52,135}

Vat photopolymerization, which includes stereolithography (SLA) and digital light processing (DLP), solidifies liquid resin by selectively curing it with a light source, such as a laser or digital projector. These methods offer high resolution, making them suitable for producing intricate and detailed designs. Photopolymer resins used in SLA and DLP offer a range of material properties, including flexibility, toughness, and biocompatibility.¹³⁶ These materials are ideal for the production of metamaterial shoes; consequently, they have been widely adopted in academic research focusing on stiffness control (Figure 6F),¹³⁷ and commercial footwear products incorporating metamaterials, including New Balance TripleCell, Asics Actibreeze, and Adidas 4DFWD (Figure 6G).^{69,138} These shoes utilize highly elastic resins, such as the Rebound and Elastomeric polyurethane (EPU) resin series. These tough and high-stretchable materials, based on polyurethane acrylate, are well-suited for lattice structures incorporated in both shoes.

3.3. Applications of 3D-printed footwear

The use of 3D printing technology has revolutionized the footwear industry by enabling the production of customized and innovative designs that were previously impossible to manufacture using traditional methods. Major footwear companies such as Adidas, New Balance, and Nike have collaborated with 3D printing companies to develop footwear to optimize athletic performance. Adidas and New Balance have integrated 3D-printed lattice midsoles into their running shoes, aiming to enhance energy return, shock absorption, and responsiveness (Figure 3E–G).¹³⁹ Nike and Raise3D took a different approach by using 3D printing to fabricate the shoe upper (Figure 7A),^{140,141} which is typically made from woven fabric. The 3D-printed upper allows enhanced flexibility and breathability without compromising durability by adding dynamic interconnection between warp and weft. Beyond midsoles and uppers, FitMyFoot, a Canadian start-up, offers custom 3D-printed insoles and sandals using 3D

scanning.¹⁴³ ASICS has also adopted a unique approach of fully 3D-printing sandals, designed for recovery and relaxation (Figure 7B). Many other companies, including Columbia and Dior, have also showcased 3D-printed shoes, highlighting the growing trend of 3D printing in the footwear industry. Recent studies have also demonstrated the long-term durability and performance of 3D-printed footwear. For example, one study conducted a fatigue test involving 700,000 loading cycles on 3D-printed footwear made from polyurethane, which is equivalent to several months of regular walking, and no permanent deformation or material hardness change was observed.¹⁴³ In another case, midsoles made from conventional EVA showed a noticeable decline in performance after 100,000 heel strikes, whereas 3D-printed midsoles retained their mechanical properties even after 1,000,000 heel strikes.¹⁴⁴ These examples demonstrate the verified durability of 3D-printed footwear and indicate its promising potential for future development.

In the field of medical applications, a number of studies have been conducted with 3D-printed custom insoles and foot orthoses. One prevalent foot disorder is flat feet, and several studies have been conducted to address the issue using 3D printing.^{25,46,47,127,145} These studies have explored the control of factors, including arch support height, stiffness, or wedge height, to redistribute plantar pressure or improve foot kinetics. Similarly, 3D printing has also been employed in the treatment of plantar fasciitis. Orthotic insoles²⁹ and Foot orthosis³¹ were designed and fabricated using 3D scanning and 3D printing (Figure 7C and D). These custom-made orthotic insoles have been effective in reducing the load on midfoot during walking and jogging, alleviating direct load from the plantar fascia. Additionally, by increasing the longitudinal arch angle, they help maintain the natural curvature of the foot arch. These results show similar efficacy for reducing pain and distributing pressure. Compared to traditional devices, 3D-printed foot orthoses have demonstrated effectiveness in supporting arch and provide less movement of the plantar flexor muscle, resulting in lower tensile strain in the plantar fascia. In the case of diabetic feet, 3D-printed insoles have been studied to provide plantar pressure offloading.^{34,36,44,45,146} These insoles aim to reduce pressure on specific areas of the foot to prevent complications associated with diabetes. Several studies have demonstrated that increasing the foot contact area to reduce peak contact pressure or incorporating porous structures which provide a gradient stiffness to effectively distribute pressure. Beyond insoles and foot orthoses, customized ankle-foot orthoses and insoles have been extensively studied and developed using 3D scanning. While many 3D-printed ankle-foot orthoses follow designs of conventional fabrication methods, some

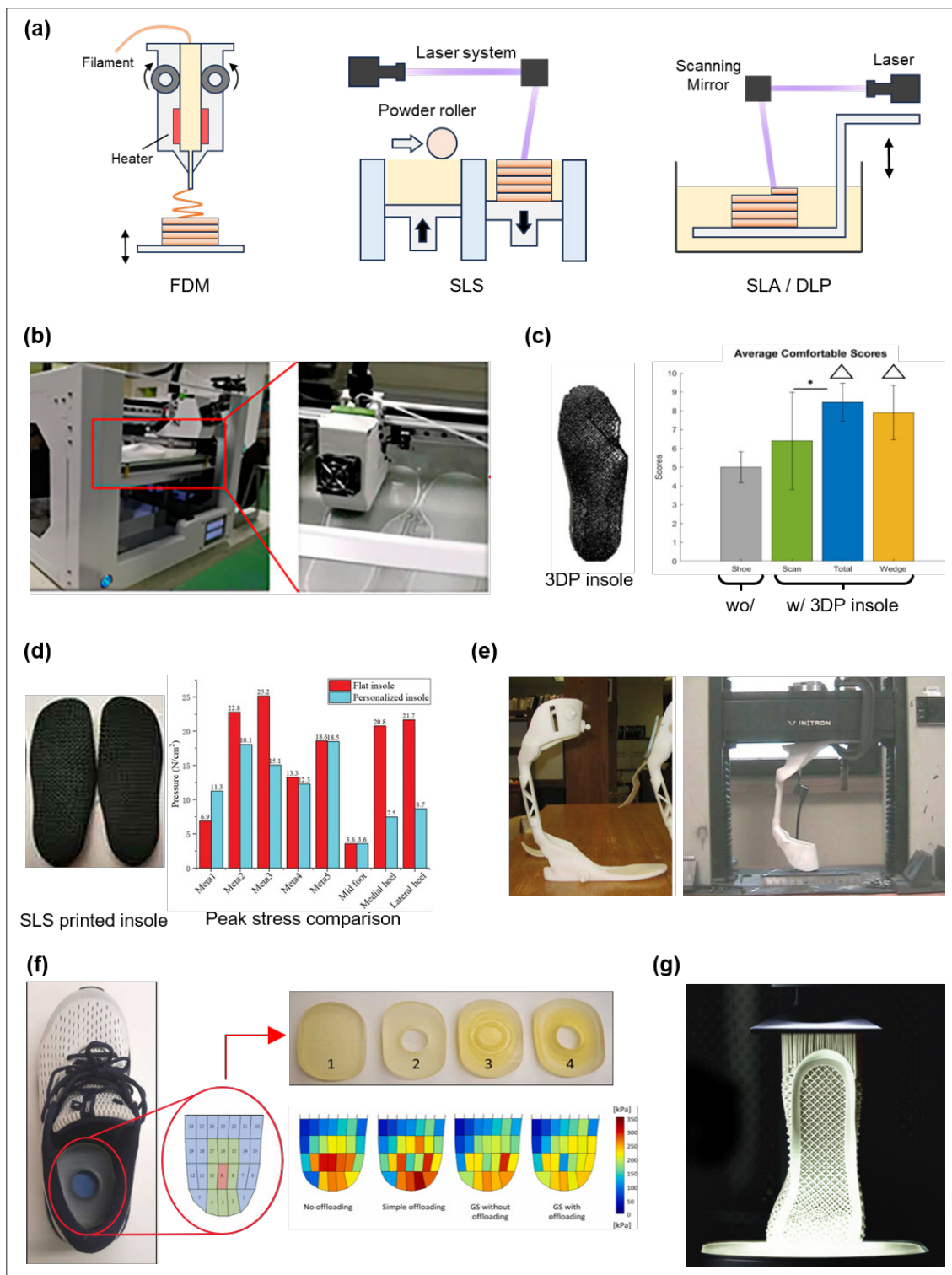


Figure 6. Fabrication methods of 3D-printed footwear. (A) 3D printing methods used to fabricate footwear. Reproduced from ref.¹³³ (B) FDM printer manufacturing shoe insole. Adapted from ref.⁴⁶ (C) 3D-printed insole using the FDM method. Adapted from ref.²⁵ (D, E) 3D-printed foot orthosis using the SLS method. Adapted with permission from ref.¹³⁴ Copyright © 2020 Taylor & Francis and ref.⁵² Copyright © 2008 IEEE. (F) Heel cup manufacturing by the SLA method. Adapted with permission from ref.¹³⁷ Copyright © 2023 Elsevier. (G) Insole printing using the SLA method. Reproduced with permission from ref.¹³⁸ Copyright © 2020, Nature. Abbreviations: 3DP, 3D-printed; DLP, digital light processing; FDM, fused deposition modeling; SLA, stereolithography; SLS, selective laser sintering.

studies have demonstrated the potential of 3D printing’s design freedom by creating an ankle–foot orthosis with adjustable stiffness in the sagittal plane, enabling a more adaptable and patient-specific orthotic solution.^{51,132,147}

In summary for athletic and clinical aspects, several studies have examined the efficacy of 3D printed footwear and found promising results. However, despite advancements in 3D-printed footwear, some researches

also report that efficacy remains insufficient due to lack of comprehensive scientific evaluations. Systematic reviews on 3D-printed insoles have yielded mixed results, with some studies reporting significant improvements in pressure distribution and biomechanical performance, while others found no major differences compared to traditional footwear.²⁴ Therefore, further research is required to establish comprehensive performance metrics

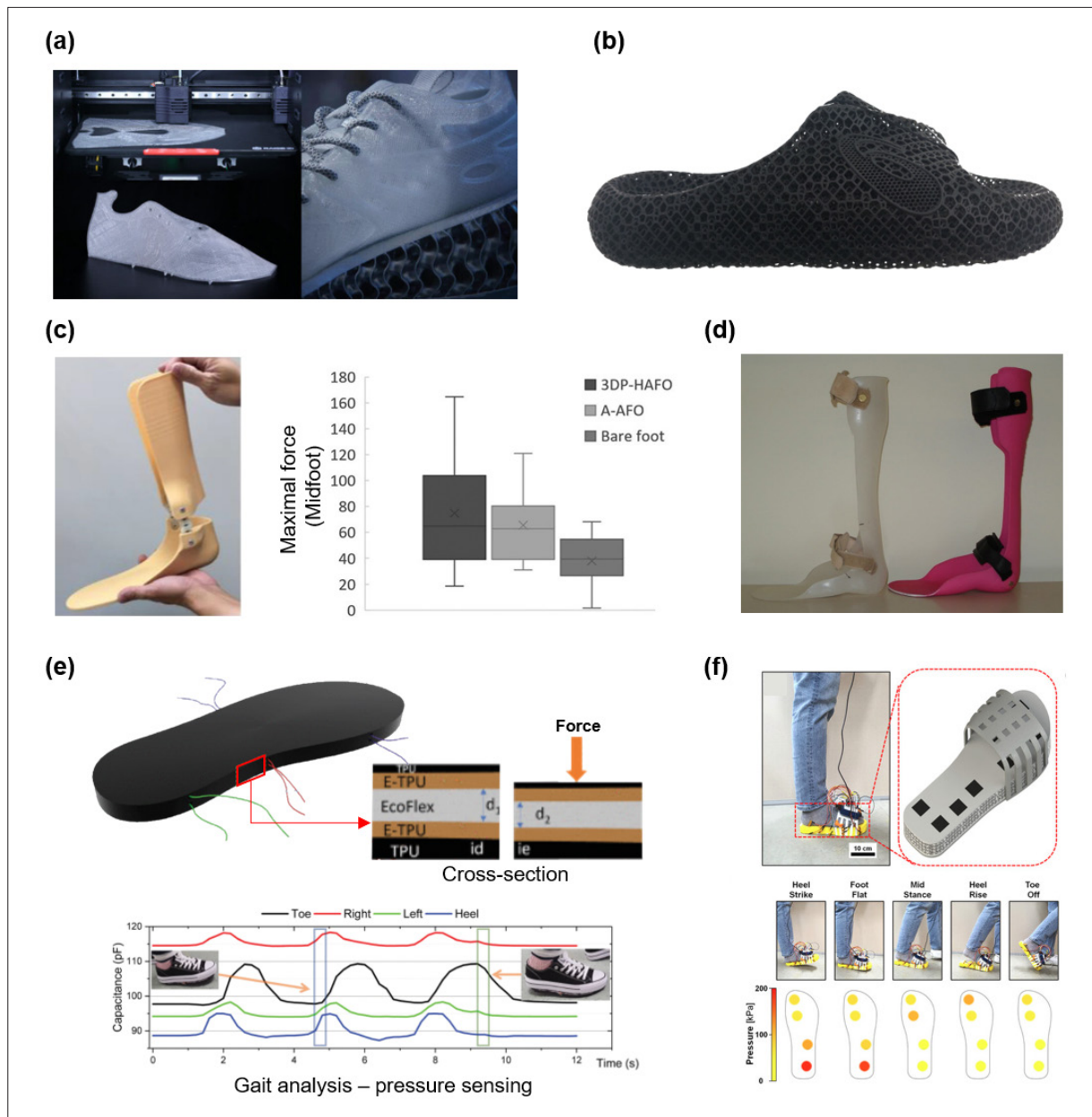


Figure 7. Applications of 3D-printed footwear. (A) Shoe upper fabricated with 3D printing. Reproduced with permission from ref.¹⁴¹ Copyright © 2025 Raise3D Technologies, Inc. (B) Commercial footwear fabricated with 3D-printed insole. (C, D) 3D-printed medical orthosis. Reproduced with permission from ref.¹⁴⁷ Copyright © 2022 Elsevier and ref.⁵¹ Copyright © 2013, © International Society for Prosthetics and Orthotics 2013. (E, F) 3D-printed smart footwear – pressure sensor-integrated footwear. Adapted from ref.⁹⁸ Copyright © 2023 Wiley-VCH GmbH and adapted with permission from ref.¹⁴⁸

and validate the effectiveness of 3D-printed footwear modifications compared to traditional ones.

Beyond conventional applications such as performance enhancement and therapeutic application, 3D printing enables novel functionalities that were previously unattainable with traditional shoe manufacturing. First, 3D-printed insoles can act as pressure sensors, providing plantar pressure measurement capabilities of up to 300 kPa without saturation (Figure 7E and F).^{98,148} These smart insoles provide real-time biomechanical feedback, offering potential applications in rehabilitation and gait analysis. Additionally, recent developments on foot pressure data suggest that data can be used to dynamically adjust stiffness within a 3D-printed shoe midsole, optimizing it to improve an individual's overall comfort level.¹²⁴ This advancement opens the door for real-time footwear adaptation, which could be particularly beneficial for individuals with biomechanical asymmetries or mobility impairments. In sum, the integration of sensing and customization capabilities into 3D-printed footwear opens up new possibilities for various applications.

4. Current limitations and future directions

While 3D printing offers unique advantages in footwear production, several limitations remain that must be resolved for broader adoption. First, further studies are needed to explore novel 3D footwear designs with enhanced performance that would be difficult to achieve without the use of 3D printing. Even though 3D printing offers high design freedom and precise personal customization, determining the optimal design for each footwear function remains a challenge. Current 3D-printed footwear designs focus more on replicating the design of conventional footwear, rather than fully exploiting the potential of 3D printing for enhanced footwear functions. This highlights the need for further research to identify optimal geometries that can effectively enhance the functions of footwear while maximizing the capabilities of 3D printing.^{24,69} Another challenge involves the limited material selection suitable for 3D-printed footwear. Footwear requires materials with low viscoelasticity to ensure rapid recovery after deformation caused by stepping, providing smooth movement between stride transitions. Previous research and commercial applications employ materials such as EPU or rebound resins to meet this requirement,⁶⁹ but the variety of materials suitable for 3D-printed footwear remains limited. This feature is closely related to another limitation, namely, relatively high unit cost and low production throughput of 3D printing. Conventional manufacturing has benefited from decades of process optimization and highly efficient mass-production systems, which significantly reduce unit cost and production time for

manufacturing. In contrast, 3D printing remains limited in terms of available materials and is mostly applied to small-scale production only, which results in comparatively higher unit costs.¹⁴⁹ These limitations pose challenges to the widespread adoption of 3D-printed footwear in industrial applications. Nevertheless, by the ongoing development of printing processes and materials, recent studies suggest that some 3D-printed footwear products may achieve cost levels comparable to those of traditionally manufactured ones, highlighting their growing economic viability.¹⁴⁹ In addition, some reports have shown that the advantages of 3D-printed footwear in customization and rapid prototyping can significantly accelerate the total product development cycle, including the design and testing process, by eliminating the need for tooling, molds, or die-specific hardware.^{125,150} Furthermore, the additive nature of the process reduces material waste, supporting its potential for more sustainable manufacturing. For example, Nike's Flyknit uses 3D printing to fabricate shoe upper, eliminating the need for cutting and stitching. This approach has been reported to reduce waste by as much as 66%, while also lowering labor costs.¹⁵¹ Based on these factors, we believe that the economic feasibility and environmental sustainability of 3D-printed footwear can be sufficiently realized in the future.

Despite several limitations, 3D printing technology holds great potential to revolutionize the way footwear is designed and manufactured. To fully utilize this potential, continued research and development efforts are essential to optimize footwear design methodologies, diversify material options, and boost manufacturing productivity. We expect that continuous advancements in 3D printing technology will drive innovation in design methodologies, material diversification, and manufacturing scalability, thereby promoting wider adoption of 3D-printed footwear with improved comfort, enhanced performance, and increased personalization.¹³⁸

5. Conclusion

3D printing has garnered significant attention as an innovative manufacturing approach for footwear, due to its capability to fabricate complex shapes, which is impossible to achieve through traditional methods.¹²² Given the multifaceted nature of footwear functions, optimal design of 3D-printed footwear requires a holistic approach considering ergonomic, biomechanical, and clinical aspects, along with the advantages and limitations of 3D printing. In this review, we have categorized the functions of footwear into three sections: protection, performance enhancement, and therapeutic applications. In terms of protection, footwear supports gait motions by impact absorption and structural support, and individual

fit. 3D printing contributes a protective function through monolithic manufacturing and customization capabilities.^{44,48} The second function, performance enhancement, focuses on improving motion efficiency and reducing energy expenditure. A key enabler of this function is adaptive stiffness control using mechanical metamaterials, which can be fabricated through 3D printing.^{69,104} Finally, therapeutic applications such as medical orthoses play a significant role in managing various foot disorders. Here, both customization and stiffness control enabled by 3D printing technology significantly improve clinical footwear applications.^{49,127} Additionally, various manufacturing methods and application fields of 3D printing are presented. This review expands on previous research by systematically integrating interdisciplinary perspectives, such as biomechanical, ergonomic, and therapeutic viewpoints, thus providing a comprehensive understanding of the capabilities and applications of additive manufacturing in footwear.

Glossary

- **Laxity:** Looseness or reduced tension in ligaments, often leading to instability.
- **Tibialis posterior:** A key muscle that supports the foot arch and prevents flatfoot deformity.
- **Pronation:** The inward roll of the foot during walking or running; excessive pronation is linked to various injuries.
- **Plantar fasciitis/fascia:** The fascia is the fibrous band under the foot; plantar fasciitis refers to its painful inflammation, often near the heel.
- **Dorsiflexion:** The motion of lifting the foot upward at the ankle, important for normal gait.
- **Osteoarthritis:** A degenerative joint disease that causes pain and stiffness, often in the knees.
- **Scoliosis:** A condition involving lateral curvature of the spine.
- **Diabetic foot:** A complication from diabetes involving nerve damage and poor circulation in the feet, increasing ulcer risk.
- **Ankle-foot orthosis:** A brace supporting the ankle and foot, often custom-molded for deformities or neuromuscular deficits.

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Conflict of interest

The authors have no conflicts of interest to declare.

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