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Application of 3D Printing Technology in Footwear Design and Manufacture – A Review of Developing Trends

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Review
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ABSTRACT
The advent of 3D printing (3DP) has garnered significant interest from both academia and industry due to its potential to revolutionize engineering, manufacturing, and through its utilization of advanced materials. Even though the application of 3D printing in footwear design and manufacture is quite appreciated, academic discourse on the subject relative to footwear design and manufacture is rather scarce compared to other fields such as pharmaceuticals, electronics and food. The purpose of this review is to explore the techniques, the application trends and the impact of 3D printing technology concerning footwear design and manufacture. Using relevant data from many relevant sources, this study uncovered that 3D printing has significantly impacted shoe design and manufacture by enhancing production efficiency, environmental sustainability, material innovation and Inter-Industry Collaborative Projects among others. Most of the major players in the footwear industry such as Nike, Adidas, Reebok and New Balance already have many footwear releases based on 3D printing. Also discussed are some specific areas in which 3D printing is being applied in footwear design and manufacture. These areas include but are not limited to the design of smart shoes, shoe lasts, complex shoe geometries, avant-garde concept shoes and so on. This study is of particular importance to stakeholders in the footwear research and design industry as it provides important information about the current trends as well as the impact of 3D printing technology on the sector.

KEYWORDS
3D printing, footwear design, footwear manufacture, design concept, smart footwear, CAD

INTRODUCTION

When purchasing shoes, one often desires customizable options, particularly for professional settings. It will therefore suffice to state that in today's consumer landscape, consumers are desirous of customized, personalized experiences [1]. However, in most cases, shoes are mass-produced and cannot be customized for customers. Shoe lasts are designed and produced in large quantities by shoe-making enterprises and factories according to the relevant shoe-low models and design standards [2].

Also For shoe brands, ensuring that shoes are as suitable as possible for their target customers is one of the main challenges they face. In most cases, shoe brands need to provide samples, which involve making patterns, cutting fabrics or leather, sewing pieces, and sending products to customers for fit studies. Multiple repetitions may be required to approve the suitability or ultimately abandon it.

Similarly, the phenomenon of fast fashion has aroused the need to apply methods that will accelerate time-to-market duration amid limited product life cycles. Of crucial importance to staying competitive is how quickly one can adapt to evolving market dynamics [3]. All these conditions require innovative technologies and that's where 3D printing of footwear is expected to revolutionize entire shoe design and production by attacking the above issues head-on as it has done in other fields.

The demonstrated possibility of applying 3D printing to produce complex components while significantly reducing material waste and lead times has established cruciality in enabling it for various vital industrial applications. Over the half-century of its existence, 3D printing technology has rapidly advanced, significantly impacting both the industrial and commercial sectors [4]. At the commencement of this century, 3D printing technology began to mature with the advancement of key technologies like Stereolithography, selective laser sintering, and fused deposition modelling.

The projection is that, in the future, when one buys shoes, it is possible to walk into a store, a machine scan the size of the feet, and then one can order a unique shoe tailored to one's comfort. Therefore, companies can now use 3D technology to decide whether to bring a product to the market without the need for physical samples or use fewer physical samples, significantly reducing the cost of abandoning styles (material, labour, and time costs). Adopting 3D technology during the sample design phase helps to reduce costs and shorten the time to market, improving process efficiency and profits.

Despite the growing interest in 3D printing for footwear design and manufacture due to the availability of affordable devices and open-source software, the technology still faces some challenges such as harmful emissions by the 3D printers, and misalignment of printed articles among others.

This paper thus sets out to discuss the various ways by which 3D printing is shaping new possibilities in footwear design and engineering, the potentials that exist in the industry as well as the existing bottlenecks that need to be tackled. The subsequent discussion is partitioned into developments in 3D printing technology, applications areas of 3D printing technology in shoe design and manufacturing and the impact of 3D printing technology on shoe design and manufacturing. Figure 1 presents a flowchart of the review process.

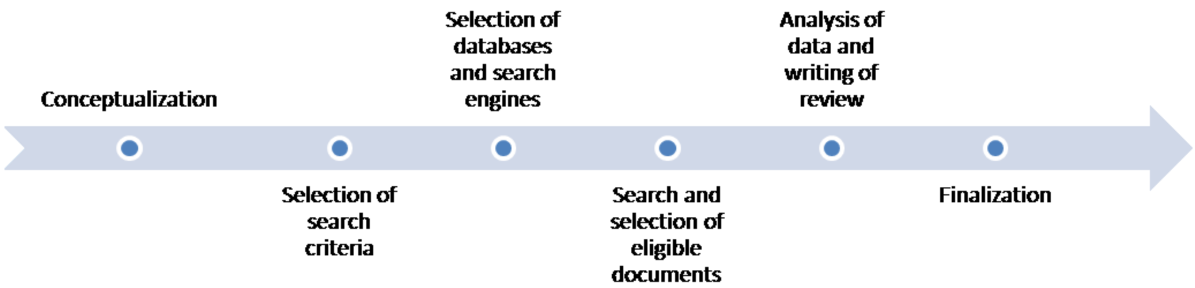

Figure 1. Framework of the review process

DEVELOPMENTS IN 3D PRINTING TECHNOLOGY

The term 3D printing is commonly synonymous with additive manufacturing, Solid Free Form technology (SFF), or Rapid Prototyping (RP) [5]. These terms refer to creating a prototype or a scale model of a physical object using 3D computer-aided design (CAD) software [6]. Printing technologies advanced quickly as personal computers became more widely used in offices and homes [7].

The literal birth of 3D printing is said to have taken place in the early 1980s. The historical development of 3D printing technology has been comprehensively dealt with in these papers where the timelines of its development have been provided [5,8]. As such this paper provides only a cursory historical background into the technology. Figure 2 shows the classification of the 3D printing technologies.

The invention of 3D printing is credited to Charles 'Chuck' Hull for formulating 3D systems and commercializing Stereolithography in 1986 [9], Shortly after, in 1988, Scott Crump from Stratasys invented another 3D printing technology known as fused deposition modelling (FDM) [10]. At the same time, two additional additive 3D printing technologies were introduced namely Solid Ground Curing (SGC) by Cubital and followed subsequently by Helisys' Laminated Object Manufacturing (LOM) [11]. Since then, many proprietary techniques have been introduced and are being used in the 3D printing industry.

According to relevant sources 3D printing technologies can be classified into about seven major categories and with over twenty sub-categories based on different criteria such as methods and materials used [5,6,8,12].

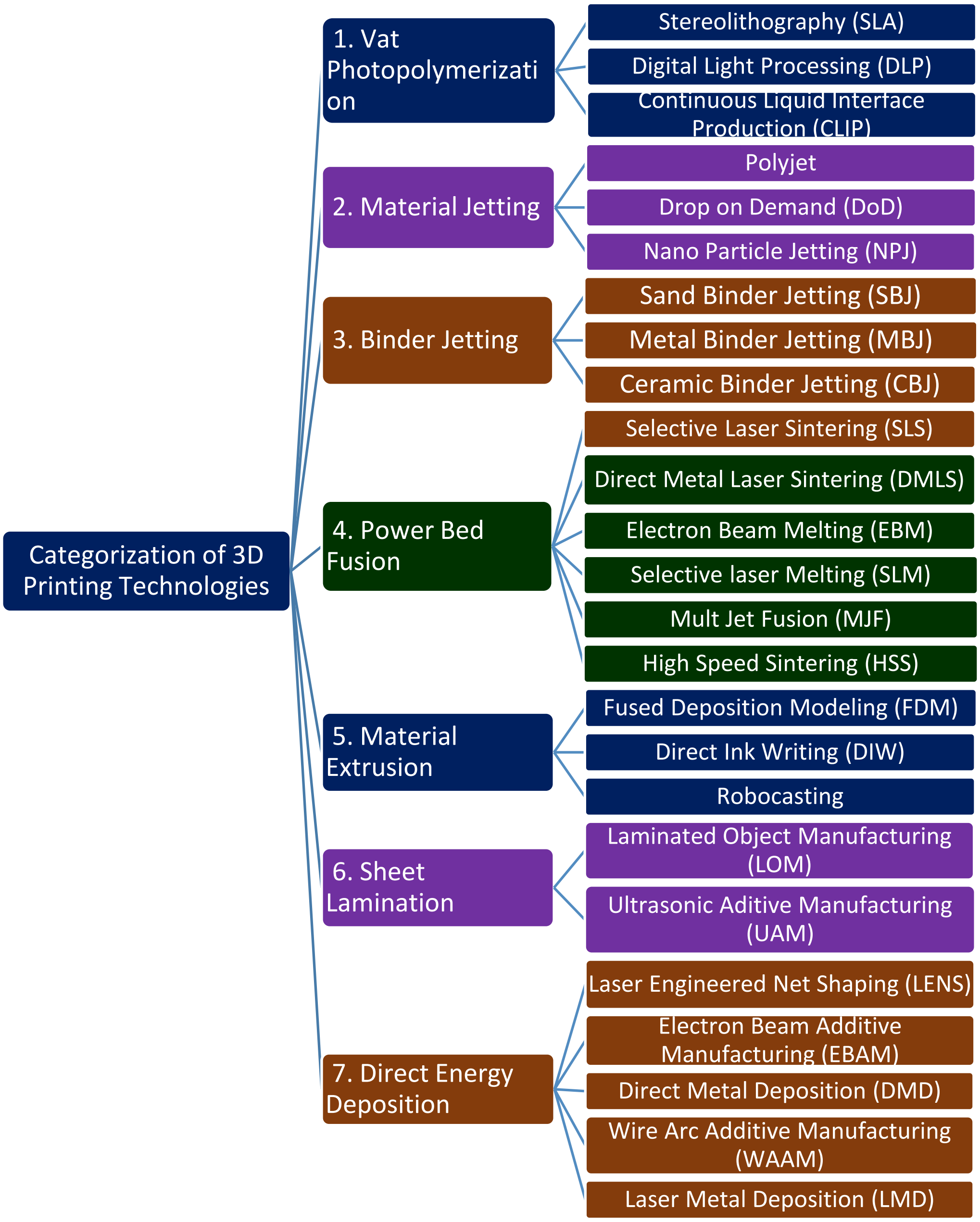

Figure 2. Classes of 3D Printing Technologies

AREAS OF 3D TECHNOLOGY APPLICATIONS IN SHOE DESIGN AND MANUFACTURING

Over the past several years, 3D printing has been advancing the boundaries of personalized footwear as well as producing shoes with special characteristics such as lightweight, intricate patterns etc. that were not possible using classical shoe-making techniques. The following are the specific areas in which 3D printing is revolutionizing the footwear design and manufacturing industry.

Functional Shoes

Functional footwear describes specifically designed and engineered footwear to ensure predefined performance requirements and/or functionality for the user. For over a decade, leading footwear brands have utilized 3D printing for prototyping and moulding. In recent years, however, there has been a growing trend of using 3D printing to create functional components for footwear. Rocker shoes and insoles help lower peak pressure in individuals with diabetes and loss of protective sensation. However, their handmade nature results in variable effectiveness.

As foot structure evolves, the areas of high peak pressure also shift. To address this, individualized algorithms and 3D printing can be used to create rockers and self-adjusting pressure-reducing insoles [13]. Reebok collaborated with BASF to develop their first line of 3D-printed shoes in 2016 [14]. In this collaboration known as the Liquid Factory, a sneaker was produced with a 3D-printed high-rebound outsole, achieving a design effect that was previously impossible with traditional rubber outsoles (shown in Figure 3(a)).

(a) (b)

Figure 3. (a) Reebok's "Liquid Speed" branded shoe [14] ; (b) Adidas' 4DFWD shoes with 3D printed midsole [15]

This design allows for greater energy conservation with each step. Also, New Balance partnered with 3D Systems to 3D print the midsoles of one of their 3D printed shoes using DuraForm Flex TPU and elastomeric powder materials through the Selective Laser Sintering (SLS) process. Cushioning elements were strategically placed in areas with higher average pressure [16].

Other similar releases are the Adidas 4DFWD airy lattice for good shock absorption shown in Figure 3(b). A new type of bionic cushion sole for paratrooper boots, designed to mimic cat paw pads, was created using additive manufacturing and has been presented by Xiao et al. [17]. Cat paw pads are believed to be crucial in reducing ground reaction forces during landing since they are the sole points of contact with the ground. 3D printing has been applied to create structures that enhance performance, such as improved traction, better shock absorption, and lightweight designs.

Rapid Prototyping

Rapid Prototyping involves creating a prototype quickly to visually and functionally evaluate a part or some part features. 3D printing allows designers to quickly create and iterate prototypes, reducing the time from concept to physical model. Timelines for Shoe modelling have been reduced from weeks to just a few hours. Additionally, 3D printing of moulds offers higher precision compared to traditional mould-making processes. Experts predict that 3D printing will streamline current supply chains by reducing the involvement of intermediaries and enabling on-demand manufacturing [18].

Shoe Last Design and Production

In instances where shoe manufacturing still requires it to be done by hand, shoe last providing ample information about the foot and size is inevitable. A shoe is a 3D representation of a foot and is used by shoemakers and manufacturers for the production of footwear. Lasts are the most crucial component in the entire process of shoe design and production [19]. Compared with the various methods such as hand carving, moulding and Computer Numerical Control (CNC) lathe machining, 3D printing of shoe lasts provides an alternative to the high-speed last manufacturing by CNC lathe machines [20].

A CNC lathe refers to computer-controlled machinery primarily used for CNC turning processes and services such as tapered turning, hard turning, spherical generation, facing, parting, knurling, drilling, grooving, and more. 3D printing also affords the designing of shoes with advanced features [21]. In their study using 3D software, they created a shoe last with 3D ease allowance features.

Customization and Personalization

Custom orthotics and insoles can be printed to match the unique contours of an individual's feet, enhancing comfort and performance. Aesthetic Customization also allows consumers to personalize colours, patterns, and even structural elements, offering unique and unprecedented footwear designs. An example is a proposed system by which consumers can customize the insole of their preferred shoe with features such as the surface characteristics, the insole pattern and the contours [22].

Complex Geometries

Designers can experiment with intricate patterns and shapes that are difficult or impossible to achieve with traditional methods. Specified footwear shapes can routinely be produced accurately and adjusted as needed, resulting in an even more efficient shoe for the consumer.

(a) (b)

Figure 4. (a) The Young Shoe [23]; (b) Sneaker with haptic coating effect [24]

Figure 4(a) shows a complex geometry 3D printed shoe referred to as the Young Shoe by designer Michael Young for the luxury footwear brand United Nude [23-24]. Michael Young is a designer who runs a creative consultancy and design agency that engages in multidisciplinary activities ranging from industrial design to technology.

Haptic coating

Haptic coating describes the instance where highly elastic soft-touch coatings are applied on articles such as footwear, toys, furniture and vehicle interiors. Haptic coatings are used to provide a distinct tactile sensation on the surface of products or objects.

Polyurethane (PU) is one of the most commonly used materials for haptic and protective coatings in the textile industry [25,26]. Screen printing has been the major technique used in applying PU-based inks in the textile industry [27].

This process is constrained due to the use of a single screen for each specific design, necessitating screen replacement when changing designs and resulting in additional waste. Additionally, achieving the desired layer thickness or multi-colour applications in screen printing requires multiple repetitions of the process, posing challenges for aligning different layers, especially for high-resolution patterns. For building up haptic and complex 3D structures on fabric or other substrates, 3D printing gets more and more relevant. Fused Deposition Modeling (FDM) and polyjet technologies have already seen some applications in the field of textiles [24].

In footwear design and manufacture, waterborne high-solid polyurethane dispersion (PUD) resins are the base for 3D printing ink formulation for haptic coatings design effects [28]. New photosensitive haptic coatings are also now being introduced to the market. China’s Fujian Huafeng New Materials Co., Ltd. and BASF Coatings GmbH are among a host of companies leading the charge [29]. These coatings are formulated with fully Waterborne Polyurethane Dispersion (PUD) resins that offer high elasticity, flexibility, and excellent bonding properties [24]. Photosensitive haptic coatings can attain not only gradual colour switches on athletic footwear but also be utilized for point-of-purchase customization. Figure 4(b) shows a Sneaker with a haptic coating effect [24].

Smart Shoe Design

A smart shoe refers to a type of footwear enabled with wearable technology, providing additional functionalities beyond the traditional purposes of protection and enhancing movement [29]. Smart shoes typically connect to smartphone apps or other user interfaces to perform tasks that standard footwear cannot accomplish. Examples include physical activity tracking, illumination and visual display, medical rehabilitation and so on.

The application of 3D printing in smart shoe design offers more flexibility in design, such as sensor placement. In a study by Binelli et al, Silicone-based inks, formulated with cellulose nano-crystals and/or carbon black fillers, were meticulously designed and utilized in the direct ink writing process to create a shoe insole demonstrator. This insole featured embedded sensors capable of measuring both normal and shear forces [30].

Trial wear pattern proofing

During the production of some types of footwear such as slippers boots, and so on, development samples are offered for wearer trial before official production. 3D printing offers the convenience of printing shoe samples directly using soft materials to test the fit between the last, upper, and sole. Also, 3D printing technology can directly produce prototype moulds, effectively reducing the shoe design cycle.

Repair and Spare Parts - Component Replacement & Repair Services

Across numerous industries, 3D printing is increasingly being utilized as a powerful solution to mitigate supply chain disruptions and improve the availability of spare and replacement parts. 3D printing enables easy production of spare parts for shoes with virtually limitless final geometries, extending their lifespan [31]. Broken or worn-out components can be reprinted and replaced, reducing the need to discard entire shoes.

An advanced technique of self-healing that could be exploited in 3D-printed footwear repair has been proposed [32]. Using a specially formulated photo-elastomer ink containing both groups of thiol and disulfide, the thiol groups facilitate a thio-lene photopolymerization during the additive manufacturing process, while the disulfide groups enable a disulfide metathesis reaction that results in a self-healing effect under temperatures of 60 °C. Experimental results demonstrated that shoe soles cut in half self-healed after about 2 hours at 60 °C.

Special component design

The various components of the footwear coordinate to provide comfort, support, and protection to the wearer's feet. 3D printing offers the flexibility of producing footwear components with special performance characteristics. Manufacturing components like midsoles for sneakers has been the most successful footwear application of 3D printing to date. Some brands employ the technology to produce sneaker midsoles and insoles, while others are exploring 3D-printed sneaker uppers and components for sandals. Nike's Flyprint was developed from a 3D-printed upper made of TPU [33]. Even though it can be worn by anyone, it is more suited for marathon runners due to its lightweight and its carbon fibre plate in the midsole increases the amount of spring in a person's step [34].

Biomimicry

The word biomimicry, also known as biomimetics, consists of bio, which means nature, and mimesis/mimicry, which means imitation. These terms refer to a way of learning from nature and incorporating its structures or solutions into human designs. Incorporating natural design principles, 3D printing can produce shoes that mimic the functionality of biological structures. An example of this is the creation of a 3D-printed biomimetic shoe using SLS technology and flexible Thermoplastic elastomer (TPE), a material known for its excellent comfort and flexibility. The design features shapes reminiscent of nature, particularly roots and vines as shown in Figure 5(a).

a)

b)

Figure 5. Earth Moc, the 3D printed biomimetic shoe [35]; (b) A bird's skull inspired hollow heel shoe [36]

Shown in Figure 5(b) is a hollow-heeled 3D-printed shoe created by Dutch fashion designer Marieka Ratsma and American architect Kostika Spaho, which was inspired by a bird's skull.

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IMPACT OF 3D PRINTING TECHNOLOGY ON FOOTWEAR DESIGN AND MANUFACTURING

3D printing has significantly impacted shoe design and manufacture, offering innovative solutions across various aspects of the industry. Here are some key areas where 3D printing has positively impacted shoe design and manufacturing.

Production Efficiency

On-demand manufacturing is a production approach that involves rapidly manufacturing parts as needed, rather than producing them in bulk for storage in a warehouse. 3D printing greatly enables this philosophy due to its rapid time-to-market capabilities. Using this philosophy, shoes can be produced as needed, reducing inventory costs and waste. Additive manufacturing processes minimize waste compared to traditional subtractive methods. Nike's Flyknit technology cuts labour costs and reduces waste by as much as 66% since there is no cutting or stitching involved.

Local Production - 3D printing facilitates local manufacturing, minimizing shipping and reducing the carbon footprint. Concurrently, the 3D printer can produce multiple models with different data specifications, greatly enhancing printing efficiency [37]. The most efficient mass-production printers can achieve an average print time of 13 to 41 minutes, allowing designers to quickly assess the appearance and design concepts of shoe samples, making them ideal for product marketing demonstrations [38].

Material Innovation – New Materials and Multi-Material Combination

The most frequently used materials for 3D printing generally include pure substances, ranging from low-melting-point plastics, polymers, and resins to high-melting-point metals, alloys, and ceramics [39]. Contemporary advances in 3D printable materials suitable for footwear have expanded their production applications. This progress has been primarily driven by close collaboration between technology providers and footwear brands. The chief material for 3D printing is the Flexible TPU (Thermoplastic Polyurethane) known for its elasticity and durability, making it ideal for producing comfortable and resilient shoe components. Currently, Bio-based polymers with eco-friendly materials properties derived from renewable sources, offer sustainability without compromising on performance and are being touted to offer great potential [40].

Graphene-infused filaments that process enhanced strength, flexibility, and electrical conductivity, are also suitable for advanced footwear designs. Soft and stretchy materials (elastomers) that are ideal for creating flexible and comfortable shoe components are being used. Recycled or

Biodegradable Filaments are being promoted to enhance sustainability while maintaining the requisite qualities for footwear production [41-42].

The use of Mechanical Meta-material Structures (MMS) - These are structures designed with special mechanical properties. A study by Amorim et al explored how different MMS can be combined to design the insole of a shoe [43]. Carbon fibre-reinforced composites offer a combination of lightweight properties and exceptional strength, making them ideal for high-performance footwear components. Additionally, 3D printing silicone elastomers using the direct ink writing (DIW) process has shown significant potential in various fields, including flexible electronics, medical devices, and soft robotics [44]. Silicone is being applied for the production of soft and cushioning parts, such as insoles and uppers [45]. Combining different materials in a single print allows for shoes with varied properties, such as rigidity in the sole and flexibility in the upper part.

Sustainability

The increase in raw material consumption and greenhouse gas emissions in the manufacturing industry is partly due to the prevalent linear economic model, also known as the "linear economy" (LE), which follows the pattern of Take, Make, Use, and Throw. To tackle the issue of overconsumption and the current environmental challenges, a more sustainable model known as the circular economy (CE) has been proposed [46]. The concept of Circular Economy (CE) transforms goods at the end of their service life into resources for others, thereby closing loops in industrial ecosystems, minimizing waste, and promoting sustainable practices [47]. The use of recyclable and biodegradable materials contributes to more sustainable shoe production.

Fashion and Innovation – Avant-garde

The avant-garde concept in footwear design denotes a break away from conventional shoe styles, pushing the boundaries of creativity, innovation, and artistic expression. Avant-garde footwear designers and brands experiment with new materials, shapes, and technologies to create shoes that are often considered wearable art. From oversized silhouettes to unique colour schemes, large soles, and elevated heels have become increasingly common.

(a) (b)

Figure 5. (a) Shock-absorbing shoe [48]; (b) 3D-printed Cryptide sneakers [49]

High-fashion designers use 3D printing to create avant-garde footwear that pushes the boundaries of traditional shoe design. Figure 5 (a) and (b) shows Avant-guard 3D printed shoes. Featured in 5(a) is a spring heel that has a mechanism which acts as a shock absorber, and gives the wearer a new walking experience while 5(b) shows a super-flexible sock up top, and a highly technical, deforming plated sole designed to leave mystifying footprints.

Inter-Industry Collaborative Projects

3D printing has enabled partnerships between technology companies and fashion brands directed at exploring new frontiers in footwear innovation. Collaboration between FitStation and HP has incorporated Materialise software for 3D design automation, print preparation, and production management. This collaboration enables footwear brands to highlight their unique brand identity by producing customized products [50]. Zellerfeld has successfully collaborated with many companies such as Louis Vuitton, Yeezy, etc.

BOTTLENECKS AND DRAWBACKS

Despite the growing interest in 3D printing due to the availability of affordable devices and open-source software, the technology still faces some challenges. 3D printing has some environmental drawbacks, primarily due to emissions produced during the printing process. Many 3D printers use plastic, which can release harmful chemicals into the air [8].

Apart from environmental concerns, many faults may result. For example, occasionally, a 3D printer may fail to finish the printing process correctly, leading to a misprint or an incomplete object. Warping may also happen when the edges of the 3D-printed shoe lift or curl during printing, resulting in a distorted final product.

Nearly all 3D printing processes rely on constructing objects layer by layer. For this process to be successful, each layer must be precisely aligned with the others. Layer misalignments lead to uneven and jagged surfaces, impacting the shoe's overall quality and appearance. These misaligned layers or shifts usually occur due to problems with the 3D printer's mechanical components [51].

Stringing or oozing in 3D printing describes the persistence of thin strings of filament between different parts of the printed article, which can reduce the quality of the print [52]. Stringing happens when the printer leaves extra filament between different parts of the shoe, resulting in unwanted webs or strings. Certain filaments can produce shoes that are too brittle or weak for regular use [53].

In their paper, Oropallo and Piegl outlined ten challenges of 3D printing ranging from shape optimization limitations, and printing errors, to a lack of technologies to model multiple materials for multi-material design and printing etc. [54]. The suggestion is that going forward, these challenges need to be addressed to ensure that the technology delivers spectacular results.

CONCLUSION

While 3D-printed shoes might seem unattractive and uncomfortable, recent innovations have demonstrated that additive manufacturing has a place in the industry. The integration of 3D printing in shoe design and manufacturing not only accelerates the development process but also opens up new possibilities for customization, sustainability, and functional enhancements.

The application of 3D printing in footwear design and manufacturing is enabling quicker market launches, offering new levels of customization, and creating remarkable new structures that were impossible with traditional manufacturing methods. Almost all notable footwear brands have unveiled 3D-printed products. Even though some bottlenecks exist, the pros of their applications far outweigh the cons. Many issues lined up for subsequent and future studies include case studies on consumer attitudes towards 3D printed footwear, the economic impact and environmental benefits of 3D printing in footwear.

Author Contributions

Conceptualization – Cui TZ and Raji RK; methodology – Raji RK; formal analysis – Han JL and Raji RK; investigation – Chen Y; resources – Chen Y; writing-original draft preparation – Cui TZ, Raji RK and Han JL; writing-review and editing – Raji RK; visualization – Chen Y; supervision – Cui TZ. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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