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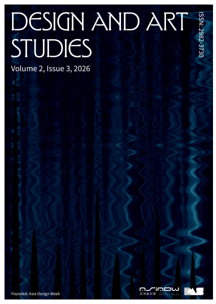

Research Article

A "Scan-to-Design" Paradigm for Footwear Innovation: Combining Reverse Engineering with Digital Manufacturing

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Abstract

In the context of Industry 4.0 and manufacturing digital transformation, the footwear industry needs to shift from experience-driven development to data-driven design and manufacturing. Rather than using finished-shoe scanning as a substitute for foot or last data, this study focuses on the reverse acquisition and digital reconstruction of complex product forms as editable design references for forward innovation. Accordingly, a Scan-to-Design framework integrating 3D scanning, reverse engineering, form redesign, and digital manufacturing is proposed and validated. A high-top canvas shoe was selected as a case object to test complex form capture. Point-cloud data were acquired using a handheld laser 3D scanner and processed in Geomagic Studio for preprocessing, registration, mesh reconstruction, and surface optimisation. Geomagic Qualify was used to quantify the reconstruction consistency and geometric fidelity of the reconstructed mesh relative to the acquired point cloud. Based on the reconstructed model, Rhino and ZBrush were applied to develop a new design with a fluidisation language, followed by 3D printing, mould fabrication, PU injection moulding, and physical assembly. Expert trial-wear evaluation showed that the prototype performed well in fit, comfort, stability, and local comfort.The results indicate that the framework connects reversereconstruction of complex forms with forward creative designand digital manufacturing, demonstrating its potential tosupport efficient design iteration, complex form development,and digitally assisted prototype fabrication.

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1. Introduction

Amid the wave of Industry 4.0 and the global digital transformation of manufacturing, the digital and intelligent upgrading of the footwear industry has become a key pathway to driving innovation and enhancing core competitiveness (Ghobakhloo et al. 2021; Zhang et al. 2024; Frank, Dalenogare, and Ayala 2019). With the deep integration of technologies such as 3D scanning, reverse engineering, computer-aided design, and additive manufacturing, digital design has become a critical enabler for the transition of footwear products from a traditional experience-driven approach to a data-driven one(Vial 2019; Kusiak 2018; Da Silveira, Borenstein, and Fogliatto 2001). Innovation in shoe styling is a core component of footwear product development, directly determining a product's market competitiveness and user experience. However, traditional footwear design and manufacturing have long relied on manual pattern drafting, experience-based mold making, and physical prototyping(Raffaeli and Germani 2011). This approach suffers from prominent challenges such as lengthy design iteration cycles, insufficient model accuracy, difficulties in realizing complex designs, and low efficiency in translating creative concepts into tangible products(Firtikiadis et al. 2024). Consequently, it struggles to meet the industry's current demands for rapid product innovation, personalized styling, and swift market responsiveness. Most existing research applies 3D scanning technology to areas such as foot morphology capture, parametric last modeling, and the development of orthopedic shoes and custom insoles, focusing primarily on addressing issues of human-foot fit and functionality. However, systematic research is scarce on the scanning, reverse engineering, and redesign of finished shoe models themselves. Consequently, the application potential of 3D scanning technology in the field of shoe design innovation remains largely untapped.

In the manufacturing industry, reverse engineering refers to a technical method that involves analyzing physical products to derive information such as structural design features and manufacturing processes. The key stages include data acquisition, data processing, model construction, and data application(Várady, Martin, and Cox 1997; Benkő, Martin, and Várady 2001). Reverse engineering technology provides a systematic approach for rapid modeling and fit verification of complex products and has been widely applied in various fields, including aerospace, automotive, and consumer goods(Bernardini and Rushmeier 2002). In foot-related research, existing studies have confirmed that 3D scanning technology can achieve high-precision geometric reconstruction of shoe lasts and foot shapes, providing a reliable data foundation for the development of customized footwear(Danckaers et al. 2024; Jones et al. 2025; Powers, Palmer, and Wilken 2022). However, current research still has certain limitations: First, research subjects are mostly concentrated on basic components such as the foot and shoe lasts, with insufficient systematic research on the scanning reconstruction and design innovation of the overall form of finished shoe styles; Second, most existing research focuses solely on optimizing the accuracy of reverse modeling, neglecting the relationship between reverse engineering and redesign innovation(Ye et al. 2008). Consequently, no effective link has been established between reverse models and forward-looking innovative design or digital manufacturing verification, resulting in a disconnect between scan data and creative design, as well as a disconnect between digital models and physical manufacturing. Third, a complete closed-loop design paradigm encompassing "shoe scanning, reverse modeling, innovative redesign, and digital manufacturing validation" has yet to be established. There is a lack of a systematic methodology for quantitative experimental validation, making it difficult to support the efficient implementation of shoe design innovations.

Accordingly, the methodological contribution of this study does not lie in proposing a new scanning or surface-reconstruction algorithm, nor in using scanning merely to reproduce an existing product in CAD. Rather, the proposed Scan-to-Design paradigm repositions the reconstructed geometry as an editable and geometrically validated design reference within a forward design process. In conventional reverse engineering and scan-to-CAD workflows, scanned data are primarily used for geometric recovery, replication, inspection, or CAD model generation. In the proposed framework, however, reconstruction is treated as an intermediate design stage rather than the endpoint: critical dimensional and morphological information can be retained as design constraints or references, while selected form features can be intentionally extracted, transformed, recombined, and developed into new product concepts. The resulting design is subsequently connected to digital prototyping and manufacturing validation. Therefore, the core contribution of Scan-to-Design lies in establishing a structured transition from reverse-acquired geometry to forward form innovation and manufacturable realization.

In summary, this study takes finished shoe styles as its research subject and proposes a "Scan-to-Design" paradigm for footwear product innovation. By integrating 3D scanning, reverse engineering, innovative redesign, and digital manufacturing technologies, it establishes a comprehensive workflow spanning from geometric data to design generation and physical validation. The study aims to address the following three core scientific and technical challenges:

Elucidate methods for preprocessing point cloud data from 3D scans of finished footwear and controlling the accuracy of reverse modeling to achieve rapid reconstruction of high-precision digital models of classic footwear styles;

Reveal the mechanism linking reverse models with forward-looking innovative design, and verify the maintainability of model accuracy and the feasibility of stylistic innovation during the redesign process.

Establish a closed-loop design process integrating 3D scanning, reverse modeling, innovative redesign, and digital manufacturing to develop a systematic, innovative design methodology tailored to the needs of the footwear industry.

2. Materials and Methods

2.1 Optical 3D Scanning

Optical 3D scanning reconstructs digital shapes by capturing the spatial coordinates of an object's surface (Sansoni, Trebeschi, and Docchio 2009; Salvi, Pages, and Batlle 2004; Altuntas 2022). Based on sensor principles, it is classified into contact and non-contact methods; the latter includes structured light scanning, laser triangulation, and photogrammetry. Structured light scanning projects stripes and captures their distortion with a camera to obtain high-density point clouds; it is fast and highly accurate, making it suitable for complex surfaces of small to medium-sized objects(Geng 2011; Cui, Tao, and Zhao 2021; Thongma-Eng et al. 2022). Laser triangulation calculates 3D coordinates by projecting and detecting reflected laser light, offering high accuracy and strong resistance to ambient light interference. Photogrammetry uses multi-angle photographs to reconstruct 3D models through feature matching; while it is cost-effective, its accuracy is relatively low (Remondino 2011). With technological advancements, scanning systems that integrate multiple methods have emerged to enhance speed and adaptability to different materials. The performance of 3D scanning is commonly evaluated by point cloud accuracy, resolution, and scanning speed (Besl and McKay 1992; Pomerleau et al. 2013; Huang et al. 2021). Accuracy refers to the deviation between the point cloud and the actual surface; Current mainstream systems can capture hundreds of thousands to millions of points per second, allowing scanning of medium-sized objects to be completed within minutes. Note that the surface material of the object and ambient lighting affect accuracy; highly reflective or transparent surfaces often require powder spraying or marking for assistance; strong light can reduce the contrast of the structured light. Table 1 compares different 3D scanning technologies. In practical applications, appropriate equipment and parameters should be selected based on product characteristics, and accuracy should be ensured through multi-angle scanning and post-processing optimization.

Table 1. Comparison of Different Optical 3D Scanning Technologies.

Comparison Criteria	**Structured Light Scanning**	**Laser Scanning**	**Photogrammetry**
Basic Principles	Projects a regular grating pattern and captures the deformation with a camera to generate a point cloud	Laser beams are emitted, and distances are measured based on reflected light or triangulation.	Calculates a 3D point cloud by matching photos taken from multiple angles
Accuracy	High Precision	High precision, suitable for measuring complex details	Lower accuracy; depends on image quality and algorithms
Resolution	High-resolution detail capture	High resolution but highly dependent on equipment	Resolution depends on pixel count, but point density is uneven
Sensitivity to Ambient Light	Sensitive to strong light; lighting must be controlled	Highly resistant to ambient light	Significantly affected by lighting conditions
Material Compatibility	Less effective on black or highly reflective surfaces	Performs well on a variety of surfaces	Difficult to match on textureless surfaces or surfaces with repetitive textures
Equipment Cost	Moderate	High	Low
Advantages	High precision, excellent detail, suitable for precision objects	Stable accuracy, resistant to ambient light, wide range of applications	Low cost, easy to use, flexible

2.2 Methods for CAD Modeling of Footwear

CAD/CAM systems are widely used in footwear design and manufacturing to improve efficiency and precision (Luximon and Goonetilleke 2004; Luximon, Goonetilleke, and Tsui 2009; Leng and Du 2006). As early as the 1970s, CAD technology was introduced into the footwear industry for last scaling and mold design(Di Roma 2017). Modern footwear CAD software features 3D modeling, last and sole design, upper development, and automatic sizing(Wrześniowska 2023). Commonly used programs include Romans CAD, ICad 3D+, Shoemaster, and ProCAM, which enable 3D design based on lasts and generate 2D patterns. ICad 3D+ is used by companies in Europe and the United States for sole and upper modeling and development; Domestic shoe manufacturers mostly use Shoemaster or in-house developed systems to implement digital workflows. Designers also utilize general-purpose 3D modeling software such as Rhino, 3ds Max, and ZBrush for conceptual design and rendering. Rhino emphasizes NURBS surface modeling, making it suitable for complex surface design; ZBrush facilitates the sculpting of upper details. The typical workflow involves first creating the last in Rhino, refining it in ZBrush, and finally generating the pattern with professional CAD software. In recent years, parametric and feature-based modeling have been introduced into footwear design. Existing research has proposed rapid modeling methods based on foot morphology, design curves, and local deformation for parametric last design and customization. These methods can generate 3D last models using key dimensions, thereby improving the efficiency of modifications and customization (Zhang et al. 2012; Wang et al. 2011). Furthermore, the integration of 3D scan data with CAD modeling has become a growing trend. By acquiring point clouds through scanning and processing them into surface or polygon models as a starting point for CAD, software such as Geomagic and PolyWorks can fit point clouds to NURBS surfaces or triangular meshes and interact with CAD software, providing a data foundation for designs that better conform to foot morphology(Huang et al. 2024; Berger et al. 2017; Matellon et al. 2024).

2.3 Scan-to-Design Workflow

The proposed workflow integrates reverse engineering with forward innovative design, following the broader concept of using reconstructed digital geometry not only for reproduction but also as a basis for subsequent design modification and innovation (Ye et al. 2008).Unlike a conventional scan-to-CAD workflow, in which geometric reconstruction is primarily treated as the output of the scanning process, the proposed Scan-to-Design workflow treats the reconstructed model as an intermediate and editable design substrate for subsequent form transformation and innovation(Silva et al. 2022; Peng et al. 2024). First, optical scanning is used to obtain a high-precision point cloud model of the physical shoe, thereby digitizing the design object. Next, the point cloud data is processed, and surface reconstruction is performed to obtain an accurate base CAD model, with model accuracy verified through deviation analysis. Building on this foundation, creative design begins: designers extract design elements and fluid surface forms from the original shoe silhouette and develop conceptual ideas through sketching. Subsequently, 3D modeling software is used to materialize the design concepts, creating a new 3D model of the shoe product, modifying the last shape, and adding functional structures and aesthetic details. After completing the digital model, a physical prototype is produced via 3D printing. The prototype is then molded and cast with elastic materials such as PU to create physical components. Finally, the prototype undergoes assembly, surface treatment, and color coating to produce a sample suitable for display and testing. This process begins with scan data and integrates precise digital modeling throughout the entire design and prototype validation process, reducing the workload associated with repeated prototyping and adjustments. The specific workflow is illustrated in Figure 1.

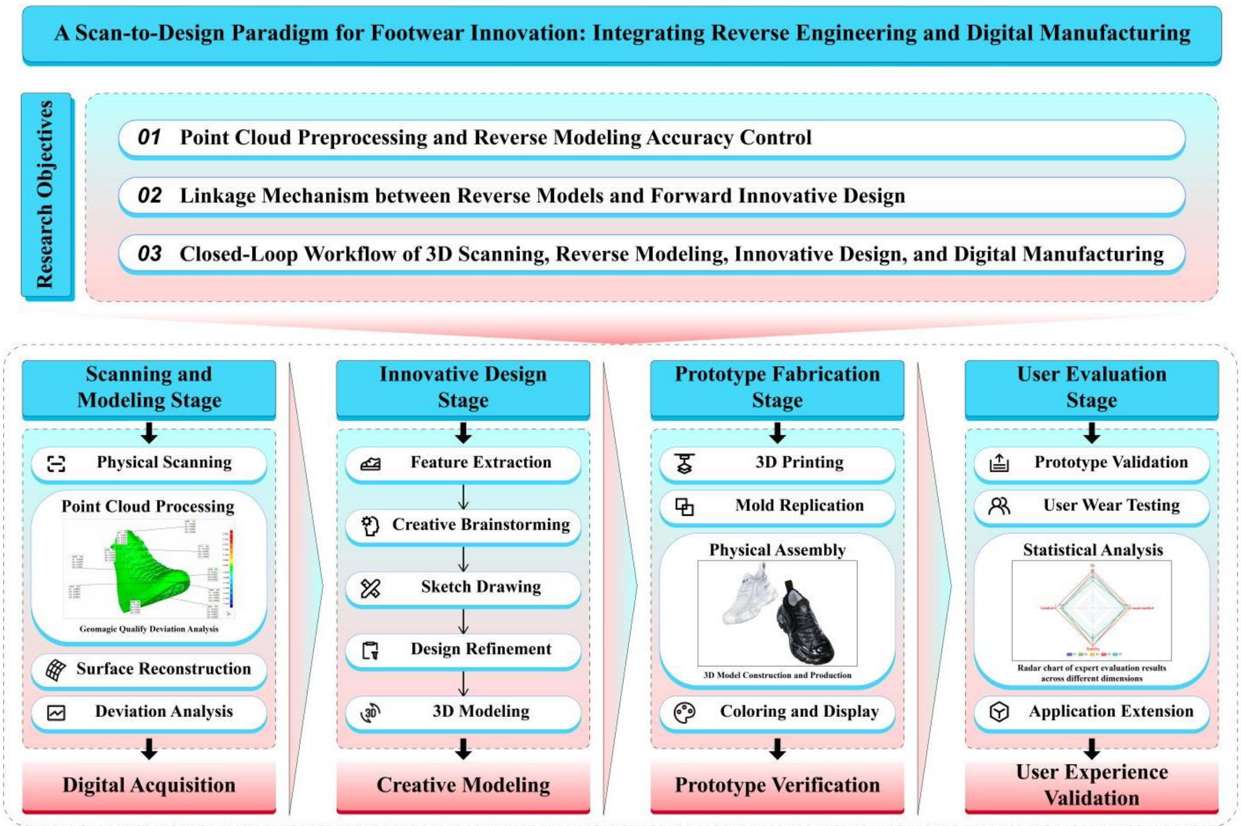


Figure 1. Design Process

3. Footwear Scanning and Data Processing

3.1 Scanning Equipment and Parameter Settings

The 3D data acquisition equipment used by the institute is the HSCAN series of handheld laser 3D scanners, which utilize multi-line laser and dual-camera synchronous acquisition technology. It offers advantages such as a compact size, ease of handheld operation, and high data accuracy. Key specifications include a scanning speed of 205,000 measurements per second, dimensions of 315 mm × 165 mm × 105 mm, a weight of 0.95 kg, and an RJ-45 network interface for high-speed data transfer. This device is suitable for scanning various complex three-dimensional objects. It is convenient to operate while handheld and uses visual markers for real-time pose tracking and spatial alignment, enabling the rapid acquisition of high-quality 3D point cloud data. It is ideal for industrial settings and product development. Before formal scanning, a quick calibration of the device must be performed to ensure the relative positional accuracy between the scanner head and the camera. Launch the accompanying software, HSCAN300-UPPS, select the quick calibration mode, and place the standard calibration plate approximately 900 mm from the scanning head. Use the laser-projected crosshair to align the center of the calibration plate. Follow the software prompts to complete data acquisition from various angles — including front-back, left-right, up-down, and forward-backward movements—to ensure the calibration plate's spatial orientation covers all angles. The system automatically analyzes and corrects positional errors, then outputs a calibration matrix to update the scanning system's geometric parameters. This process eliminates systematic errors between devices, improving the accuracy of subsequent point cloud stitching and the geometric consistency of model reconstruction. The specific scanning equipment is shown in Figure 2.

Figure 2. Scanning Equipment and Parameter Configuration

3.2 Selection of the Design Sample

The shoe design project adopted the theme of "Paying Homage to Classics," selecting iconic brand models for reinterpretation. First, we conducted a comparative analysis of classic products from the world's top ten mainstream footwear brands based on four metrics: market share, search volume, social media buzz, and secondary market transaction data. From this analysis, we selected 10 candidate models that demonstrated both strong market performance and iconic design, as shown in Figure 3. Next, the colors in the shoe images were converted to black, white, and gray to eliminate the influence of color on the perceived aesthetic of the products. A total of five industry experts with over three years of footwear design experience were invited to score and rank the candidate shoe models using the Likert scale across four dimensions: structural integrity, neutrality of the last, classic design, and complexity of details. As shown in Table 2, the Converse Chuck Taylor All Star high-top canvas shoe scored highest across most dimensions, demonstrating the best structural clarity and design distinctiveness. It was ultimately unanimously recommended as the subject for scanning and innovative design in this study. This shoe model exhibits a high degree of stylistic distinctiveness. Its overall structure consists of many recognizable elements, such as the sole, upper, toe cap, lace eyelets, and side logo. With clear geometric lines and distinct components, it is well-suited for 3D modeling and subsequent detail optimization. Additionally, the last's shape is relatively neutral, accommodating most foot types while retaining organic curves, making it an ideal base model for innovative design.

Figure 3. Shoe Samples

Table 2. Shoe Sample Scorecard.

Style Number	Structural Integrity (Average Score)	Last Neutrality (Average Score)	Classic Design (Average Score)	Detail Complexity (Average Score)	Overall Average Score	Ranking
1	4.00	3.80	4.00	4.00	3.95	3
2	3.20	2.20	3.40	2.40	2.80	8
3	4.00	3.00	3.80	4.20SS	3.75	4
4	4.40	4.60	3.60	3.40	4.00	2
5	4.20	3.40	4.40	4.20	4.05	1
6	3.60	4.20	3.60	2.40	3.45	5
7	2.00	2.60	2.00	2.80	2.35	10
8	2.60	3.00	1.80	2.20	2.40	9
9	3.00	3.00	3.20	3.60	3.20	6
10	3.20	2.40	3.00	2.80	2.85	7

3.3 Point Cloud Data Acquisition and Processing

During scanning, the shoe prototype is secured at the center of a rotating turntable so that its primary dimensional axis is perpendicular to the horizontal plane. First, the shoe is scanned externally; the scanner rotates once around the turntable to capture a point cloud of the shoe's circumferential outer surface. Next, the scanning angle is adjusted to capture easily obscured areas—such as the upper opening and outsole edges—from both the top and bottom (Fig. 4a). To capture the shape of the shoe's interior cavity, after scanning the exterior, several frames of point clouds are captured with the shoe opening facing toward the camera, and these are merged with the overall model using software. After three rounds of scanning from different angles, a relatively complete point cloud of the shoe body was obtained. The acquired dataset contained approximately 460,000 points and provided broad coverage of the visible upper contour and sole surface, as shown in Fig. 4b.

After data collection is complete, the raw point cloud is imported into Geomagic Studio software for preprocessing and model reconstruction. First, the noise filtering function is used to remove isolated outliers, and approximately 0.5% of anomalous points are eliminated based on a distance threshold. Subsequently, the manual clipping tool is used to remove irrelevant point clouds, such as the workbench and sole support structures, retaining only the target shoe upper data. Next, the multi-view scan data undergoes registration and global optimization to minimize cumulative errors between different viewpoints. Based on this, the surface reconstruction module was used to generate a triangular mesh model: first, the point cloud was triangulated to construct an initial mesh; then, local structures were optimized through mesh smoothing and hole-filling operations; finally, a complete and continuous triangular mesh model of the shoe upper was obtained (Fig. 4c).

During the process of multiple data acquisitions and stitching, the original point cloud may still be subject to local errors caused by factors such as occlusion, lighting, and material reflection, thereby affecting the geometric accuracy of the reconstructed model. Therefore, to quantify the geometric consistency between the reconstructed mesh and the acquired point-cloud data, this study employed the 3D Deviation Analysis module of Geomagic Qualify 2013. Based on the Cloud-to-Mesh (C2M) method commonly used in reverse-engineering workflows, the deviation between the reconstructed mesh and the acquired point cloud was evaluated.

First, the Iterative Closest Point (ICP) algorithm is used to perform high-precision rigid-body registration of the original point cloud (reference data) and the reconstructed triangular mesh model (test data) within a unified coordinate system. This algorithm solves for the optimal rigid transformation by iteratively searching for corresponding point pairs and minimizing the sum of the squares of the Euclidean distances between them,The ICP algorithm was used to rigidly register the acquired point cloud and the reconstructed mesh within a common coordinate system, thereby minimizing residual rigid misalignment prior to the deviation analysis (Besl and McKay 1992; Pomerleau et al. 2013; Rusinkiewicz and Levoy 2001).

After registration, the shortest Euclidean distance from each of the 465,328 data points in the original point cloud to the reconstructed mesh surface is calculated. Specifically, for any point $p_i(x_i, y_i, z_i)$ in the point cloud, the nearest point q on the reconstructed mesh surface S is identified, and the deviation is defined as:

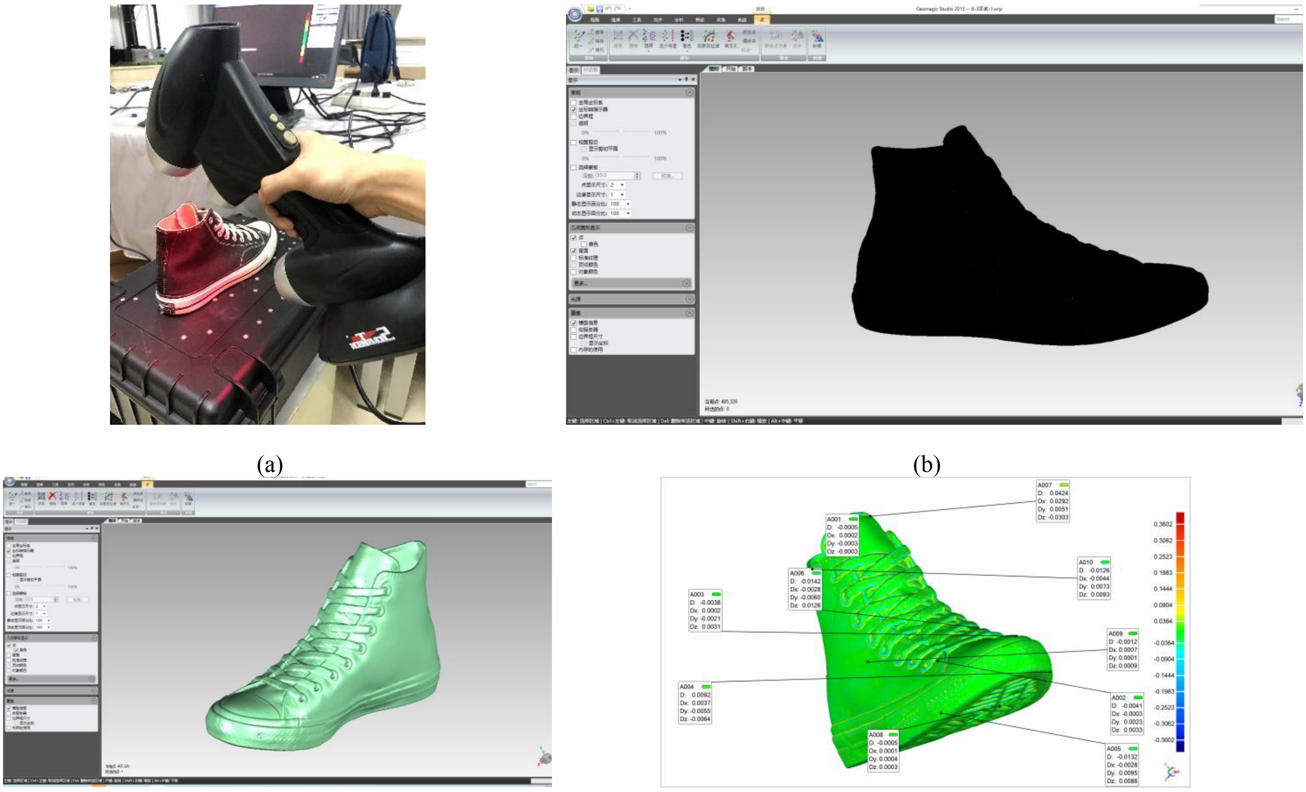
$$D_i = \min_{q \in S} \| p_i - q \| \quad (1)$$

In this equation, D_i represents the shortest Euclidean distance from point p_i to the reconstructed mesh surface, reflecting the local deviation of that point in geometric space. Based on the distribution of distances for all points, a statistical analysis is performed to assess the overall accuracy of the reconstructed model. The root mean square error (RMSE) is used to measure the overall level of geometric deviation, and its formula is:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} D_i^2} \quad (2)$$

Here, n represents the total number of points in the point cloud. Additionally, by combining the maximum positive deviation and the maximum negative deviation, we analyze the distribution characteristics of the error extremes to assess the geometric deviation in local regions of the model.

The calculation results show that the root mean square error (RMSE) between the overall point cloud and the reconstructed mesh is 0.0239 mm, with deviations primarily falling within the range of ± 0.0364 mm. This indicates that the overall error of the model is small, and no significant systematic bias was observed. In the deviation visualization cloud map, most areas appear green, indicating high geometric consistency between the reconstructed mesh and the original point cloud; deviations are primarily concentrated in structurally complex or easily obscured areas, such as the edges of the sole and the lace holes, which may be caused by incomplete local scanning or interpolation errors during the reconstruction process (Fig. 4d).The calculation results showed a Cloud-to-Mesh RMSE of 0.0239 mm, with most deviations falling within ± 0.0364 mm. The deviation map showed close geometric agreement between the reconstructed mesh and the acquired point cloud, while relatively larger local deviations were mainly observed around structurally complex or partially occluded regions, such as the sole edges and lace holes. These results indicate a high level of reconstruction consistency and geometric fidelity relative to the acquired point-cloud data. It should be noted that, because the reconstructed mesh was generated from the same scanning data, the reported deviations represent reconstruction/fitting consistency rather than an independent measurement of absolute geometric accuracy relative to the physical shoe. Nevertheless, the analysis provides a quantitative assessment of the geometric consistency of the reconstructed model used as the digital reference for subsequent redesign.



(a) (b)

(C) (d)

Figure 4. (a) HSCAN physical scanning; (b) Acquisition of model point cloud data; (c) Model processing in Geomagic Studio; (d) Deviation analysis in Geomagic Qualify

4. Innovative Shoe Design Based on Scanned Data

4.1 Sketch Design and Creative Concepts

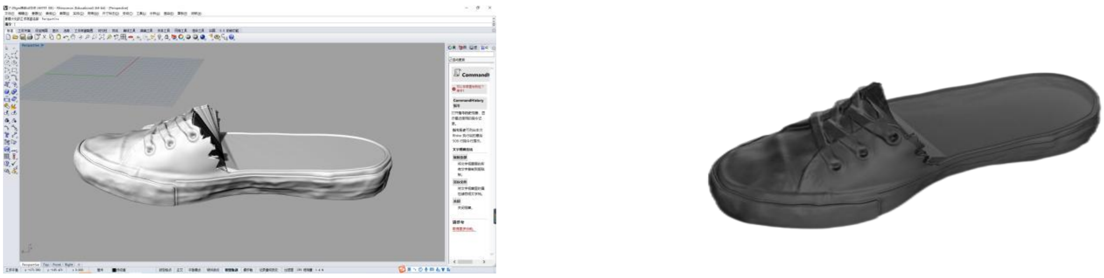
After obtaining high-precision 3D scan data of the shoe upper, we explored innovative design solutions based on classic shoe silhouettes, primarily through sketching. First, we systematically analyzed the design language of the Converse Chuck Taylor high-top canvas sneakers, extracting their representative visual elements: the rubber toe cap, flattened sidewalls, perforated laces, and the nearly rectangular proportions of the shoe body. These elements form the morphological foundation of the prototype and provide both constraints and inspiration for subsequent design innovations. The design innovation breaks away from traditional structural and geometric limitations, reimagining the form under the theme of “fluidization” and reshaping the visual order through curved constructions that blend localized melting with overall fusion. Multiple rounds of freehand sketching based on the last side view were conducted to emphasize the continuity and fluidity of the form. The impact protection strip on the outer sole was transformed into a wavy, jelly-like rubber surface, simulating the material characteristics of natural cooling after hot melting; the upper structure was reorganized so that traditional partition boundaries transitioned via curved lines, forming a continuous, undulating surface texture; simultaneously, a “melted droplet” form extending from the toe to the heel was introduced, expressing a biomimetic visual rhythm within asymmetrical streamlines. Matte leather and glossy rubber were used to enhance the visual tension of the fluid effect. Finally, 10 test subjects were invited to evaluate the design. The group included 5 footwear product designers, 3 sports shoe consumers and potential buyers, and 2 design faculty members and students. A solution with a clear direction and consistent design language was selected, as shown in Figure 5.

Figure 5. Final Concept Sketch

4.2 Modeling and 3D-Printed Part Fabrication

During the digital modeling phase, this study employed a multi-software collaborative approach using Rhino, Geomagic Studio, and ZBrush to complete the 3D modeling of the innovative shoe design. For complex free-form surface areas such as the toe box and heel, local NURBS surfaces were first converted into polygonal meshes using Geomagic Studio's polygon editing functions. Subsequently, sculptural detail editing was performed in both Geomagic and ZBrush — for instance, enhancing the three-dimensionality of the toe cap area and optimizing the concave transitions of the shoe's flowing surfaces. After editing, the model was exported back to Rhino to complete high-precision surface fitting. Leveraging Rhino's precise modeling capabilities, we directly implement innovative details on the scanned model of the original shoe—reconstituted through reverse engineering: based on design sketches, we sketch key contour lines on the last surface, including the new upper top line, the streamlined raised boundary curves on the sides, and the sole thickness profile; we extrude the cross-sectional curves of the shoe's forefoot along the sides to fully preserve the core characteristics of the fluid-inspired design; For the sole section, considering the structural wrapping requirements in later stages, a sweep modeling method was used to generate a transition surface with gradually varying thickness along the shoe edge, fully preserving the assembly and stitching curves from the forefoot to the heel (Fig. 6a).

To evaluate the manufacturability of the shoe's core components and explore their compatibility with conventional molding processes, the digital model was used for prototype fabrication and subsequent mold development: the printed model, based on a reverse-engineered monocoque component, fully preserves the "fluidic" upper contour, toe box structure, and lace hole arrangement, balancing both stylistic accuracy and structural strength to fulfill the dual functions of "design language expression and prototype fabrication." After parametric refinement in Rhino, an STL file of the integrated upper structure was exported and used to produce a prototype via stereolithography (SLA) 3D printing. A high-hardness resin was selected as the printing material to ensure fabrication precision and post-processing performance. After printing, the part undergoes IPA cleaning and secondary UV curing to produce a physical prototype with a smooth surface and sharp edges (Bikas, Stavropoulos, and Chryssolouris 2016; Muir et al. 2022; Li, Jung, and Lee 2024). Subsequently, the 3D-printed prototype serves as the master mold for creating a metal production mold, marking the transition to PU injection molding for mass production: multi-station automatic injection equipment is used to complete the foaming and molding of the polyurethane material, with single-injection accuracy controlled within ±1 g. This process offers advantages such as high operational efficiency, excellent molding consistency, and superior shock absorption, making it suitable for the small-batch production of complex, customized shoe designs. The final result is a PU shoe upper component that meets design specifications (Fig. 6b), achieving a complete closed-loop process from digital design to physical mass production(Zhang et al. 2023; Galan, Narayan, and Markovs 1990).



(a) (b)

Figure 6. (a) 3D model creation; (b) PU components based on 3D printing and mold manufacturing

4.3 Physical Assembly and Concept Display

After completing the production of all components, the prototype was physically assembled and presented in multiple color schemes. First, the PU outsole was bonded to the corresponding upper components using industrial adhesive to prevent delamination during testing. Accessories such as laces and insoles were then attached, and their tightness was adjusted to achieve the desired aesthetic. The final physical product and fitting results are shown in Figure 7. The first style is a black-and-white contrast design, featuring a black canvas upper paired with a translucent white jelly midsole. It retains the original lace holes and seam structure to enhance the classic silhouette's recognizability, resulting in a clean, trendy overall look. The second style is the Fluid Iridescent design, featuring a midsole made of blue-to-purple gradient iridescent PU material. It exhibits a strong jelly-like fluidity and a metallic mirror finish, creating a striking visual impact. The third style is the Metallic Leather design, with an upper crafted from metallic gold leather and a thick, fluid sole. It blends streetwear aesthetics with a retro texture, showcasing a harmonious contrast and fusion of materials. The fourth style is the Tech Cold Gray series, featuring a monochromatic design with the upper and sole in matching tones, accented by highly reflective elements for a distinctly futuristic look.

Figure 7. Actual product images

4.4 User Experience Validation Design

To preliminarily evaluate the usability of shoe designs based on 3D scan data in real-world wearing scenarios, this study employed an expert trial-wearing evaluation method to validate the prototype shoes. This validation primarily focused on assessing the structural rationality and wearing experience of the products from a professional perspective. The study invited the aforementioned five professionals with experience in footwear product design to participate in the trial evaluation, designated as "E1, E2, E3, E4, and E5". During the trial, participants performed tasks such as static standing, normal walking, simple turns, and short-distance movement to simulate everyday wearing scenarios. After the trial, participants provided subjective evaluations of the prototype shoes based on their experience.

The evaluation criteria encompassed four dimensions: fit, comfort, stability, and localized comfort. Each dimension included multiple evaluation items and was scored using a 5-point Likert scale, where 1 indicated "strongly disagree," and 5 indicated "strongly agree"; higher scores indicated more positive evaluations. Descriptive statistical analysis of the evaluation results was conducted to calculate the mean and standard deviation for each dimension, reflecting the overall performance of the sample shoes across different performance dimensions and the consistency of the evaluations. The evaluation results are shown in Tables 3 and 4, and Figure 8 presents radar charts of expert evaluation results across different dimensions based on the analysis.

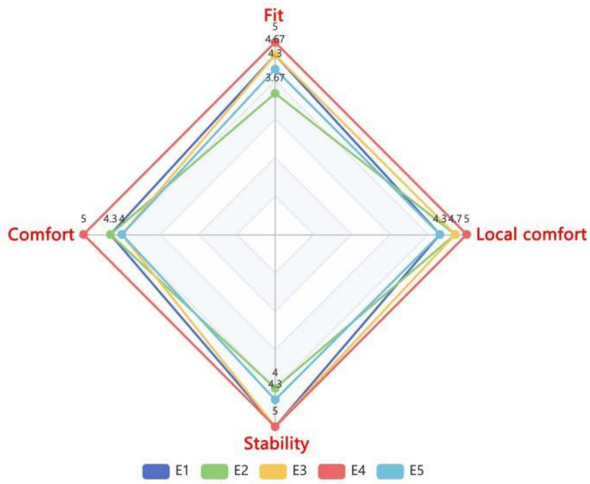


Figure 8. Radar chart of expert evaluation results across different dimensions

Table 3. Statistical results of expert trial wear evaluations.

Expert	Fit	Comfort	Stability	Local comfort
E1	4.67	4.33	5.00	4.33
E2	3.67	4.33	4.00	4.67
E3	4.67	4.00	5.00	4.67
E4	5.00	5.00	5.00	5.00
E5	4.33	4.00	4.33	4.33

Table 4. Mean and standard deviation analysis.

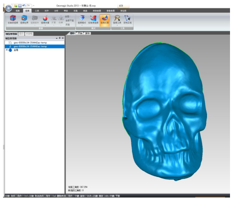
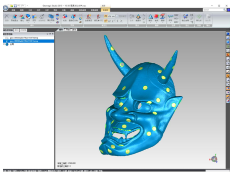
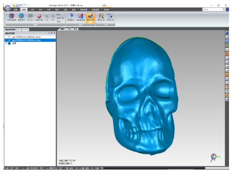
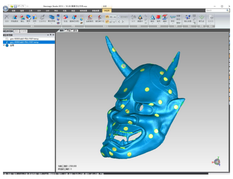
Evaluation Dimension	Mean	Standard Deviation
Fit	4.47	0.48
Comfort	4.33	0.39
Stability	4.67	0.47
Local comfort	4.60	0.27

5. Discussion

5.1 Advantages in Industrial Applications

Compared to traditional footwear development models that rely on experience-based mold-making and manual prototyping, 3D scanning-based digital modeling methods have brought about fundamental transformations in footwear and apparel design, including greater design freedom, personalized design, and digital manufacturing. Using classic shoe styles as a case study, this research established a comprehensive design methodology that integrates high-precision point cloud capture, surface reconstruction, deviation verification, and reverse engineering. Through 3D printing and mold replication, this approach provides a digitally connected pathway for translating creative designs into physical prototypes. Experiments confirm that the synergistic application of 3D scanning with CAD platforms such as Rhino and Geomagic enables the precise construction of digital models that align with foot anatomy and design semantics. The closed-loop "scan-model-manufacture" process fundamentally redefines traditional footwear manufacturing logic, providing technical support for the personalized, parametric, and standardized development of footwear and apparel products. Based on this process, this study not only completed the innovative redesign of Converse's classic shoe models but also validated the method's versatility through cross-category applications: by scanning and reconstructing skulls and Prajna masks to extract stylistic elements, these were applied to the development of footwear, bags, and apparel. The resulting designs were showcased at Guangzhou Fashion Week and received market recognition, expanding the design boundaries of body scanning technology in the fashion industry. Its core advantages over traditional approaches are as follows, as shown in Table 5.

Table 5. Analysis of the Advantages of Industry Applications Based on the Scan-to-Design Workflow.

Applications	Scan body measurements	Product photos	Design-to-Manufacturing Pathway
Footwear			The 3D model of the skull obtained through scanning undergoes morphological simplification and surface reconstruction to extract its iconic contours and structural features, which are then integrated into the outsole and upper designs as the core design language. ① Design Freedom: Achieves complex biomimetic curved surfaces that are difficult to produce using traditional craftsmanship, expanding the boundaries of shoe design; ② Personalized Design: Transforms cultural symbols into exclusive shoe designs; ③ Digital Manufacturing: Enables small-batch production of complex shapes through 3D printing and injection molding
Handbags	 		Scan the full-scale geometric forms of the Prajna mask, extract features such as facial contours and horns via reverse engineering, and reconstruct them into the main structure of the bag, preserving the mask's visual distinctiveness and structural integrity. ① Design Freedom: Faithfully reproduce the mask's complex three-dimensional structure at a 1:1 scale, breaking through the limitations of traditional flat bag design; ② Personalized Design: Transforming cultural IP into exclusive bag designs; ③ Digital Manufacturing: Using 3D printing to create molds for customized small-batch production
Apparel			Scan the mask model, simplify the form to extract 2D outlines and 3D structures, and convert them into garment print patterns and three-dimensional decorative elements to integrate into apparel design. ① Design Freedom: Transform complex 3D forms into 2D and 3D designs suitable for apparel, expanding the boundaries of fashion design; ② Personalized Design: Achieve a personalized fusion of cultural symbols and apparel; ③ Digital Manufacturing: Directly integrate digital models with printing and 3D printing processes to rapidly bring designs to life.

5.1.1 Freedom of design

Traditional footwear design is constrained by the physical limitations of shoemaking techniques, mold machining, and manual carving, making it difficult to achieve complex structures — particularly irregular surfaces, gradient geometries, and biomimetic structures. 3D scanning technology can capture high-precision point clouds of existing shoe models or reference objects, fully reproducing their complex geometric details and providing accurate references for subsequent modeling and creative transformations. Building on this foundation, designers use modeling software such as ZBrush to reconstruct surfaces and apply artistic modifications, incorporating innovative stylistic elements like fluidity, melting, and folding to achieve highly personalized structural expressions. This technology transforms footwear design from "manufacturable" to "conceivable," expanding the design space and artistic possibilities.

5.1.2 Custom Design

Traditional shoe lasts typically rely on standard sizing systems, which fail to adequately account for individual foot shape variations, resulting in poor fit and comfort. 3D scanning can quickly capture the geometric data of a user's foot to create parametric shoe lasts or reference models, enabling truly user-centric design. Additionally, by scanning users' existing footwear, preferred styles, and cultural symbols, "co-creation design" can be achieved, directly translating user preferences into product aesthetics. This bottom-up design approach enhances product personalization, increases user engagement, and fosters a customized experience for consumers.

5.1.3 Digital Manufacturing

As the front-end interface of the digital supply chain, 3D scanning technology is highly integrated with processes such as CAD modeling, rapid prototyping, and mold replication, forming a fully digitalized system characterized by data-driven operations, model-based control, and intelligent responsiveness. Compared with workflows that rely heavily on repeated physical prototyping, the integration of scanning, digital modeling, and additive manufacturing provides a more continuous digital pathway from geometric acquisition to prototype realization. Because design modifications can be implemented directly on the digital model before physical fabrication, the proposed workflow has the potential to reduce unnecessary physical iterations and improve the efficiency of design development. In addition, the reconstructed and redesigned digital models can be transferred to processes such as 3D printing and mold fabrication, facilitating rapid prototype verification and digitally assisted small-batch production. Although the present study did not quantitatively compare development time or cost with conventional footwear development methods, the completed prototype-to-mold-to-PU fabrication process demonstrates the practical manufacturability of the proposed workflow.

5.2 Broader Design Applicability of the Scan-to-Design Workflow

Beyond footwear development, the Scan-to-Design workflow may be particularly useful in design scenarios where existing physical forms need to be transformed into editable digital references for subsequent innovation. First, it provides a practical pathway for redesigning legacy or existing products when original CAD data are unavailable, allowing physical geometry to be digitally reconstructed and reused as a basis for further development. Second, the approach is particularly relevant to products containing complex free-form, organic, or highly irregular surfaces that are difficult to reproduce efficiently through conventional parametric modeling alone. Third, physical objects such as artifacts, natural forms, or existing products can be captured as morphological references, from which selected geometric characteristics may be extracted, transformed, and recombined into new product forms. In these contexts, Scan-to-Design functions not simply as a digitization process, but as a bridge between physical form references, creative transformation, and digital manufacturing. Nevertheless, its applicability depends on the characteristics of the scanned object, material properties, and the requirements of the target product, and further validation across different product categories is still required.

6. Conclusions

Taking the classic Converse high-top canvas sneakers as the subject of this study, we developed and validated an innovative "Scan-to-Design" paradigm for footwear that integrates 3D scanning, reverse engineering, styling redesign, and digital manufacturing. This approach establishes a fully integrated, closed-loop process spanning from the scanning of physical shoes, high-precision digital model reconstruction, and fluid-inspired styling innovation, to 3D-printed prototyping, mold replication, and final mass-production validation. From the perspectives of reconstruction consistency, design iteration, the realization of complex forms, and manufacturing feasibility, this study demonstrates the practical potential of the proposed digital workflow for footwear design and development. Rather than establishing quantitative superiority over conventional footwear development processes, the results show that the Scan-to-Design paradigm can connect physical form acquisition, digital redesign, prototype fabrication, and mold-based manufacturing within an integrated workflow. It provides practical technical solutions and methodological support to address industry pain points—such as insufficient design accuracy, lengthy iteration cycles, and difficulties in implementing complex creative concepts—thereby driving personalized innovation and digital transformation in the footwear and apparel industry.

In terms of digital model reconstruction, this study extends the application of scanning from foot and last morphology to the reverse reconstruction of an entire finished shoe. Geomagic Studio was used for point-cloud preprocessing, registration, and mesh reconstruction, while Cloud-to-Mesh deviation analysis was employed to quantify reconstruction consistency relative to the acquired point-cloud data. The resulting RMSE of 0.0239 mm and the concentrated deviation distribution indicate close agreement between the reconstructed mesh and the source point cloud(Danckaers et al. 2024; Jones et al. 2025; Powers, Palmer, and Wilken 2022). These values should be interpreted as measures of reconstruction/fitting consistency rather than independent evidence of absolute geometric accuracy relative to the physical shoe. The reconstructed model nevertheless retained the principal surface morphology and detailed geometric features represented in the acquired scan data, providing a quantitatively characterized digital reference for subsequent redesign.

From a methodological perspective, the key distinction of the proposed Scan-to-Design paradigm lies in the role assigned to the reconstructed model. In conventional reverse engineering and scan-to-CAD workflows, reconstruction primarily serves geometric recovery, replication, inspection, or the generation of editable CAD models. In contrast, Scan-to-Design treats the reconstructed geometry as a validated design substrate for subsequent forward innovation. Selected geometric characteristics can be retained as morphological references or dimensional constraints, while other features are deliberately transformed according to a new design language. Therefore, the methodological contribution does not arise from scanning or CAD reconstruction alone, but from the structured transition from reverse-acquired geometry to creative form transformation and manufacturable verification. Based on high-precision reverse-engineered models, the study extracted classic Converse design elements and distilled a "fluid" design language. Through collaborative modeling in Rhino and ZBrush, it successfully realized complex aesthetic forms—such as molten surfaces, continuous skin textures, and asymmetrical droplet shapes — that traditional craftsmanship could not achieve. While retaining the ergonomic advantages of the original last, this approach has completely broken free from the technical constraints of traditional shoemaking, expanding the boundaries of footwear design from "manufacturable" to "conceivable." Unlike existing research that limits 3D scanning to functional applications such as orthopedic shoes and custom insoles, this study fully taps into the potential of reverse-engineered models for aesthetic innovation, providing a new pathway for the personalized and artistic development of footwear products.

In terms of industrial implementation, this study did not merely establish a digital design workflow, but rather a complete closed-loop digital manufacturing system integrated with actual production. By utilizing stereolithography (SLA) 3D printing to produce resin prototypes, creating metal molds, PU injection molding, combined with an automated dosing process with precision controlled, we completed the assembly and validation of four innovative shoe models in different colorways, The successful fabrication of the redesigned components through SLA prototyping, mold preparation, and PU injection molding demonstrates the manufacturability of the proposed workflow and its potential compatibility with digitally assisted small-batch production. Furthermore, by extending the methodology of form scanning, reverse engineering, and stylistic redesign to shoe, bag, and apparel designs featuring skull and Hannya mask motifs, and successfully showcasing these at fashion weeks, These exploratory cross-category applications suggest that the Scan-to-Design paradigm has potential applicability beyond footwear, particularly for wearable and consumer products involving complex physical form references. Further validation across different product categories is required to establish its broader generalizability.

However, the study still has certain limitations. Validation was conducted only on shoes made of conventional canvas and rubber materials; the stability of point cloud acquisition and modeling for highly reflective, fully transparent, and ultra-flexible materials still needs optimization, and mesh reconstruction algorithms for complex openwork and extremely irregular structures require further improvement. Additionally, the study only validated the design-to-manufacturing process and did not conduct wear comfort or durability evaluations on a large sample of users. Future research could focus on optimizing point cloud processing and surface fitting algorithms, expanding the methodology to diverse applications such as athletic shoes and orthopedic footwear, and integrating 3D foot scan data to combine shoe reverse innovation with ergonomic foot adaptation, thereby establishing a more comprehensive end-to-end personalized footwear design system.

Data Availability Statement

Data generated during this study are included in this published article.

Conflicts of Interest

The authors declare no conflicts of interest.

Author's Contributions

Conceptualization, Y.J. and L.Z; methodology, L.Z., Y.J., and Y.W.; software, L.Z. and Y.J.; validation, Y.J., Y.W., and P.G.; formal analysis, L.Z. and Y.W.; investigation, L.Z.; resources, P.G.; data curation, Y.J., Y.W.; writing — original draft preparation, P.G., Y.J., and L.Z.; writing—review and editing, G.P. and Y.W.; visualization, Y.J and L.Z; supervision, P.G., L.Z and Y.J.; project administration, P.G.; funding acquisition, P.G. L.Z and Y.J. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Written informed consent was obtained from all subjects involved in the study.

References

Altuntas, C. 2022. Point Cloud Acquisition Techniques by Using Scanning LiDAR for 3D Modelling and Mobile Measurement. Paper presented at the Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.

Benkő, P., R. R. Martin, and T. Várady. 2001. "Algorithms for Reverse Engineering Boundary Representation Models."

Comput.-Aided Des. 33:839-851. https://doi.org/10.1016/S0010-4485(01)00100-2.

Berger, M., A. Tagliasacchi, L. M. Seversky, P. Alliez, G. Guennebaud, J. A. Levine, A. Sharf, and C. T. Silva. 2017. "A Survey of Surface Reconstruction from Point Clouds." *Comput. Graph. Forum* 36:301-329. https://doi.org/10.1111/cgf.12802.

Bernardini, F., and H. Rushmeier. 2002. "The 3D Model Acquisition Pipeline." *Comput. Graph. Forum* 21:149-172. https://doi.org/10.1111/1467-8659.00574.

Besl, P. J., and N. D. McKay. 1992. "A Method for Registration of 3-D Shapes." *IEEE Trans. Pattern Anal. Mach. Intell.* 14:239-256. https://doi.org/10.1109/34.121791.

Bikas, H., P. Stavropoulos, and G. Chryssolouris. 2016. "Additive Manufacturing Methods and Modelling Approaches: A Critical Review." *Int. J. Adv. Manuf. Technol.* 83:389-405. https://doi.org/10.1007/s00170-015-7576-2.

Cui, B., W. Tao, and H. Zhao. 2021. "High-Precision 3D Reconstruction for Small-to-Medium-Sized Objects Utilizing Line-Structured Light Scanning: A Review." *Remote Sens.* 13:4457. https://doi.org/10.3390/rs13214457.

Da Silveira, G., D. Borenstein, and F. S. Fogliatto. 2001. "Mass Customization: Literature Review and Research Directions." *Int. J. Prod. Econ.* 72:1-13. https://doi.org/10.1016/S0925-5273(00)00079-7.

Danckaers, F., K. Stankovic, T. Huysmans, B. G. Booth, and J. Sijbers. 2024. "Foot Shape Assessment Techniques for Orthotic and Footwear Applications: A Methodological Literature Review." *Front. Bioeng. Biotechnol.* 12:1416499. https://doi.org/10.3389/fbioe.2024.1416499.

Di Roma, Annalisa. 2017. "Footwear Design. The paradox of" tailored shoe" in the contemporary digital manufacturing systems." *The design journal* 20 (sup1):S2689-S2699.

Firtikiadis, Lazaros, Athanasios Manavis, Panagiotis Kyratsis, and Nikolaos Efkolidis. 2024. "Product design trends within the footwear industry: A review." *Designs* 8 (3):49.

Frank, A. G., L. S. Dalenogare, and N. F. Ayala. 2019. "Industry 4.0 Technologies: Implementation Patterns in Manufacturing Companies." *Int. J. Prod. Econ.* 210:15-26. https://doi.org/10.1016/j.ijpe.2019.01.004.

Galan, R. J., T. Narayan, and R. A. Markovs. 1990. "Novel Polyurethane Shoe Sole Systems Having Superior Low Temperature Flex Properties." *J. Cell. Plast.* 22:35-45. https://doi.org/10.1177/009524439002200104.

Geng, J. 2011. "Structured-Light 3D Surface Imaging: A Tutorial." *Adv. Opt. Photonics* 3:128-160. https://doi.org/10.1364/AOP.3.000128.

Ghobakhloo, M., M. Fathi, M. Iranmanesh, P. Maroufkhani, and M. E. Morales. 2021. "Industry 4.0 Ten Years On: A Bibliometric and Systematic Review of Concepts, Sustainability Value Drivers, and Success Determinants." *J. Clean. Prod.* 302:127052. https://doi.org/10.1016/j.jclepro.2021.127052.

Huang, X., G. Mei, J. Zhang, and R. Abbas. 2021. "A Comprehensive Survey on Point Cloud Registration." *Remote Sens.* 13:1629. https://doi.org/10.3390/rs13081629.

Huang, Z., Y. Wen, Z. Wang, J. Ren, and K. Jia. 2024. "Surface Reconstruction From Point Clouds: A Survey and a Benchmark." *IEEE Trans. Pattern Anal. Mach. Intell.* 46:9727-9748. https://doi.org/10.1109/TPAMI.2024.3429209.

Jones, P. J., A. V. Rowlands, M. J. Davies, D. Webb, C. L. Gillies, and A. Shah. 2025. "Foot Measurements From Three-Dimensional Scans: Elinvision 3DST Reliability." *J. Foot Ankle Res.* 18:e70070. https://doi.org/10.1002/jfa2.70070.

Kusiak, A. 2018. "Smart Manufacturing." *Int. J. Prod. Res.* 56:508-517. https://doi.org/10.1080/00207543.2017.1351644.

Leng, J., and R. Du. 2006. "A CAD Approach for Designing Customized Shoe Last." *Comput.-Aided Des. Appl.* 3:377-384. https://doi.org/10.1080/16864360.2006.10738476.

Li, J., I. Jung, and S. Lee. 2024. "Analysis of Plantar Pressure of Midsole Prepared by 3D Printed Biomimetic Structures with Different Densities." *Fashion Text.* 11:35. https://doi.org/10.1186/s40691-024-00402-x.

Luximon, A., and R. S. Goonetilleke. 2004. "Foot Shape Modeling." *Hum. Factors* 46:304-315. https://doi.org/10.1518/hfes.46.2.304.37346.

Luximon, A., R. S. Goonetilleke, and K. L. Tsui. 2009. "Shoe-Last Design Innovation for Better Shoe Fitting." *Comput. Ind.* 60:621-628. https://doi.org/10.1016/j.compind.2009.05.015.

Matellon, A., E. Maset, A. Beinat, and D. Visintini. 2024. "Surface Reconstruction from SLAM-Based Point Clouds: Results from the Datasets of the 2023 SIFET Benchmark." *Remote Sens.* 16:3439. https://doi.org/10.3390/rs16183439.

Muir, B. C., J. S. Li, Y. F. Hudak, G. E. Kaufman, S. Cullum, and P. M. Aubin. 2022. "Evaluation of Novel Plantar Pressure-Based 3-Dimensional Printed Accommodative Insoles-A Feasibility Study." *Clin. Biomech.* 98:105739. https://doi.org/10.1016/j.clinbiomech.2022.105739.

Peng, Y., Y. Wang, Q. Zhang, S. F. Chen, M. Zhang, and G. Li. 2024. "Custom Orthotic Design by Integrating 3D Scanning and Subject-Specific FE Modelling Workflow." *Med. Biol. Eng. Comput.* 62:2059-2071. https://doi.org/10.1007/s11517-024-03067-2.

Pomerleau, F., F. Colas, R. Siegwart, and S. Magnenat. 2013. "Comparing ICP Variants on Real-World Data Sets." *Auton. Robots* 34:133-148. https://doi.org/10.1007/s10514-013-9327-2.

Powers, O. A., J. R. Palmer, and J. M. Wilken. 2022. "Reliability and Validity of 3D Limb Scanning for Ankle-Foot Orthosis Fitting." *Prosthet. Orthot. Int.* 46:84-90. https://doi.org/10.1097/PXR.0000000000000066.

Raffaeli, Roberto, and Michele Germani. 2011. "Advanced computer aided technologies for design automation in footwear industry." *International Journal on Interactive Design and Manufacturing (IJIDeM)* 5 (3):137-149.

Remondino, F. 2011. "Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning." *Remote Sens.* 3:1104-1138. https://doi.org/10.3390/rs3061104.

Rusinkiewicz, S., and M. Levoy. 2001. Efficient Variants of the ICP Algorithm. Paper presented at the Third International Conference on 3-D Digital Imaging and Modeling.

Salvi, J., J. Pages, and J. Batlle. 2004. "Pattern Codification Strategies in Structured Light Systems." *Pattern Recognit.* 37:827-849. https://doi.org/10.1016/j.patcog.2003.10.002.

Sansoni, G., M. Trebeschi, and F. Docchio. 2009. "State-of-the-Art and Applications of 3D Imaging Sensors in Industry, Cultural Heritage, Medicine, and Criminal Investigation." *Sensors* 9:568-601. https://doi.org/10.3390/s90100568.

Silva, R., A. Veloso, N. Alves, C. Fernandes, and P. Morouco. 2022. "A Review of Additive Manufacturing Studies for Producing Customized Ankle-Foot Orthoses." *Bioengineering* 9:249. https://doi.org/10.3390/bioengineering9060249.

Thongma-Eng, Punrit, Pokpong Amornvit, Patcharawan Silthampitag, Dinesh Rokaya, and Attavit Pisitanusorn. 2022. "Effect of Ambient Lights on the Accuracy of a 3-Dimensional Optical Scanner for Face Scans: An In Vitro Study." *Journal of Healthcare Engineering* 2022 (1):2637078.

Várady, T., R. R. Martin, and J. Cox. 1997. "Reverse Engineering of Geometric Models-An Introduction." *Comput.-Aided Des.* 29:255-268. https://doi.org/10.1016/S0010-4485(96)00054-1.

Vial, G. 2019. "Understanding Digital Transformation: A Review and a Research Agenda." *MIS Q.* 43:118-144. https://doi.org/10.25300/MISQ/2019/12118.

Wang, J., H. Zhang, G. Lu, and Z. Liu. 2011. "Rapid Parametric Design Methods for Shoe-Last Customization." *Int. J. Adv. Manuf. Technol.* 54:173-186. https://doi.org/10.1007/s00170-010-3144-y.

Wrześniowska, Karolina. 2023. "Shoe Last Customization: A Systematic Review." *International Journal of Engineering & Technology Innovation* 13 (3).

Ye, Xiuzi, Hongzheng Liu, Lei Chen, Zhiyang Chen, Xiang Pan, and Sanyuan Zhang. 2008. "Reverse innovative design—an integrated product design methodology." *Computer-aided design* 40 (7):812-827.

Zhang, C., Y. Chen, H. Chen, and D. Chong. 2024. "Industry 4.0 and Its Implementation: A Review." *Inf. Syst. Front.* 26:1773-1783. https://doi.org/10.1007/s10796-021-10153-5.

Zhang, S., Q. Gao, Y. Zhang, X. Sheng, Z. Miao, J. Qin, G. Zhang, and X. Shi. 2023. "3D Printing Thermoplastic Polyurethane Hierarchical Cellular Foam with Outstanding Energy Absorption Capability." *Addit. Manuf.*

76:103770. https://doi.org/10.1016/j.addma.2023.103770.

Zhang, Y., A. Luximon, A. K. Pattanayak, and M. Zhang. 2012. "Shoe-Last Design Exploration and Customization." *J. Text. Inst.* 103:541-548. https://doi.org/10.1080/00405000.2011.589576.