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ORIGINAL

DEVELOPMENT AND APPLICATION OF A VISUALIZATION PLATFORM FOR SPORTSWEAR DESIGN BASED ON VR TECHNOLOGY

Miao Yu

Faculty of Art and Design, Shanghai Business School, Shanghai, 200235, China.
E-mail: watercolorskirt81@163.com

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ABSTRACT

The digital transformation of the fashion industry has become a critical driver for innovation, especially in the sportswear sector, which demands high levels of functionality and aesthetics. This study presents the development and application of a VR-based visualization platform designed to revolutionize sportswear design. The platform integrates modular design, dynamic simulation, and real-time 3D modeling to enhance efficiency, flexibility, and user experience. Modular design principles enable rapid prototyping and customization, while dynamic simulation powered by Finite Element Analysis (FEA) ensures precise performance evaluation. The platform also features a consumer co-creation module, allowing real-time interaction between designers and users for personalized customization. By combining advanced technologies and sustainable practices, this platform addresses key challenges in the sportswear industry, such as efficiency, environmental impact, and user-driven design. Experimental validation with professional designers demonstrated significant improvements in design efficiency, realism, and consumer engagement. This research provides a novel solution for the digitalization of the sportswear industry and lays the groundwork for future innovations in intelligent and sustainable apparel design.

KEYWORDS: Virtual Reality (VR), Sportswear Design, 3D Modeling, Sustainable Design.

1. INTRODUCTION

With the rapid development of the global digital economy, digital transformation has become a critical driving force for the upgrading of traditional industries, including the fashion design industry. Sportswear, as a domain that combines functionality and aesthetics, places high demands on design precision and innovation (Göknur, 2010). However, traditional design methods largely rely on 2D sketches, manual pattern-making, and repetitive trial-and-error processes. These approaches are not only inefficient but also heavily resource-dependent, making it difficult to respond swiftly to the growing market demands for personalization and diversity.

As consumer expectations for comfort, functionality, and personalized experiences in apparel continue to rise, traditional design methods are increasingly inadequate. These challenges have created a vast space for the application of digital technologies, particularly Virtual Reality (VR), to introduce innovative solutions(Al-Ghaili et al., 2022). VR technology, with its immersive, interactive, and conceptual characteristics, offers a transformative approach to sportswear design. In the context of sportswear, VR enables designers to create and refine designs in a three-dimensional virtual environment while simulating real-world scenarios to test and optimize dynamic performance (Li et al., 2024). This design approach allows for intuitive visualization of garments in different conditions, enabling designers to optimize styles, fabrics, and functionality comprehensively at an early stage.

As a result, development cycles can be shortened, and production costs reduced. Moreover, VR technology supports virtual try-on and display features, providing consumers with an immersive shopping experience while enhancing brand competitiveness and customer engagement (Sarakatsanos et al., 2024). Sportswear, as a highly functional and application-diverse subfield, demands greater sensitivity to technology and innovation. Beyond meeting ergonomic and biomechanical requirements, sportswear must also align with fashion trends in appearance. Traditional design methods struggle to meet these demands effectively.

By simulating real-world sports scenarios, VR technology enables a comprehensive demonstration of a garment's three-dimensional structure and dynamic adaptability, offering new possibilities for sportswear design. Furthermore, a visualization platform powered by VR technology facilitates seamless collaboration among designers(Papahristou, 2016), consumers, and businesses, achieving efficient cross-departmental coordination and personalized customization. Figure 1 illustrates an example of how VR technology is applied in fashion design (Westra, 2018).

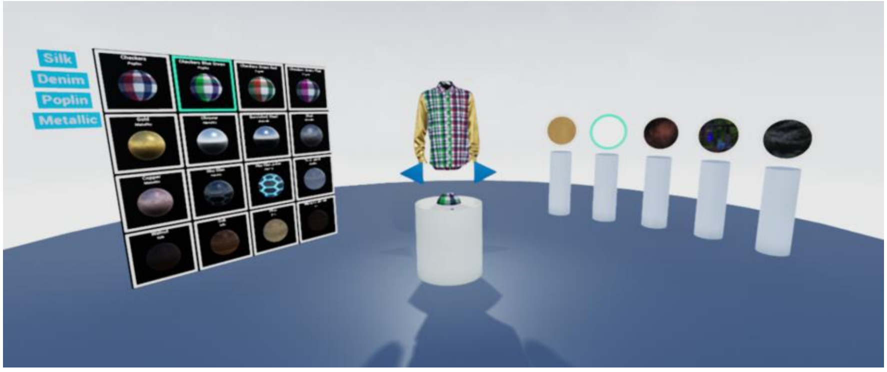

Figure 1: Schematic Diagram of VR Technology Application in Fashion Design (Westra, 2018)

From a societal perspective, the digital transformation of the fashion industry not only enhances design efficiency but also reduces resource consumption and environmental pollution. Traditional garment design processes often require significant fabric and labor investments during pattern-making and testing stages(Ma et al., 2023). The integration of VR technology significantly reduces material usage and production time, contributing to green and sustainable development in the industry (Salah et al., 2019). Through digital design platforms, consumers can also participate more actively in the design process, expressing personalized needs and driving the shift toward co-creation and customization in consumption models(Liu & Liu, 2017).

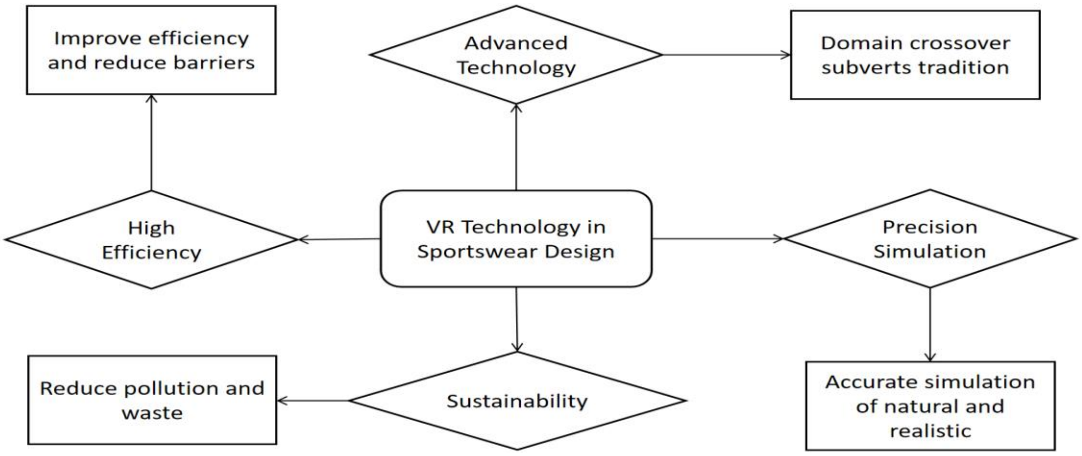

Figure 2: The Advantages of VR Technology in Sportswear Design.

This study aims to develop a visualization platform for sportswear design based on VR technology. This platform supports designers in rapidly creating garment styles and conducting dynamic tests in a three-dimensional virtual environment while enabling consumers to engage in virtual try-ons and provide real-time feedback(Sheng et al., 2023). The primary objectives of this research are to enhance the efficiency and quality of sportswear design, provide designers and enterprises with innovative, intelligent, and digital tools, and strengthen consumer experience through user participation and feedback, ultimately driving digital transformation in the fashion industry. This research introduces several key innovations:

Integration of Modular Design with VR Technology: The study combines modular design principles with VR technology to develop a rapid design methodology tailored to sportswear. Modular design enhances the reusability of garment components and allows for diverse style generation through parameter adjustments, significantly reducing the design cycle. This approach addresses the limitations of traditional design methods in terms of flexibility and efficiency, offering a novel technical solution for the fashion industry (Firtikiadis et al., 2024).

Consumer-Centric Visualization Platform: The developed platform prioritizes user participation by establishing a real-time interaction mechanism between consumers and designers. Unlike the traditional one-directional design process, this platform enables consumers to directly participate in the design process(Liu & Liu, 2017), expressing their preferences through virtual try-ons and personalized customization. This bidirectional interaction model not only improves user experience but also provides enterprises with precise market feedback, facilitating differentiated brand development.

Real-World Application and Validation: The research validates the platform through its application in the digital design processes of sportswear brands, exploring its feasibility and effectiveness in commercial environments. The platform integrates functions such as virtual prototyping, dynamic try-on, presentation, and interactive design, offering a comprehensive digital solution for enterprises. This combination of theoretical research and practical application enhances the scientific rigor of the study and provides valuable insights for the industry (Goel et al., 2023).The VR-based visualization platform for sportswear design combines technological innovation with optimized user experience, significantly improving design efficiency, reducing resource consumption, and meeting the growing consumer demand for personalized apparel. This research not only offers a digital transformation solution for the sportswear industry but also introduces new perspectives for theoretical studies in fashion design. As VR technology continues to advance and its application scenarios expand, its potential in the fashion industry will be further unlocked, driving the sector toward greater intelligence and sustainability.

2. Platform Requirements and Functional Design

2.1 Unique Requirements and Trends in Sportswear Design

Sportswear design is highly distinctive, with demands and trends that differ significantly from other types of apparel (Bramel, 2005). At its core, sportswear prioritizes functionality. Unlike everyday clothing, sportswear must meet high-performance requirements for specific scenarios, such as moisturewicking, elasticity, durability, and breathability (Harlin et al., 2020). In intense physical activities, garments need to fit closely to the body to minimize friction and avoid restricting movement, thereby enhancing athletic performance. Additionally, achieving dynamic fit is a crucial design goal, requiring designers to optimize the structure of garments in three-dimensional space to ensure the wearer's freedom of movement and comfort during activities. An example of sportswear design is shown in Figure 3.

Figure 3: Example of Sportswear Design

On the other hand, the market for sportswear is increasingly leaning toward diversity and personalization. Consumers not only demand functional performance but also seek garments that reflect their individuality and sense of fashion (Kim et al., 2002). The growing popularity of athleisure style has further fueled the adoption of sportswear, necessitating a balance between functionality and aesthetics. Furthermore, with the rapid advancement of digital technologies, the sportswear industry is accelerating its transition toward digitalization and intelligence, making virtual reality (VR) an essential tool for designers to enhance efficiency and shorten development cycles.

2.2 Functional Module Design

To address the complexity of sportswear design, the platform integrates multiple functional modules, covering the entire process from inspiration generation to dynamic virtual try-on. These modules collaborate seamlessly, providing an efficient and intuitive design experience for both designers and consumers. The Inspiration Generation Module serves as the starting point of the design process. By integrating an extensive library of garment styles and design materials, it offers diverse creative support for designers. Designers can search for keywords or utilize system recommendations to access inspiration materials. The system also leverages deep learning techniques to generate novel design elements, such as innovative patterns and color combinations. This feature alleviates creative bottlenecks, significantly improving early-stage design efficiency. The Design and Editing Module forms the core of the platform. Using advanced 3D modeling technology, designers can make real-time adjustments to garment patterns, cutting lines, and fabric textures within a virtual space(Choi, 2022). The platform's parameterized adjustment feature allows designers to quickly generate multiple design variations, catering to diverse needs. Real-time rendering technology ensures that the design effects, including fabric gloss, texture, and dynamic behavior, are presented immediately, enabling designers to finalize complex optimizations within a short timeframe. The Dynamic Try-on and Simulation Module combines virtual try-on with dynamic performance testing to help designers identify and address potential issues during the early stages of design. By inputting body parameters, users can generate a 3D human model and observe the garment's dynamic performance in a virtual environment. Finite Element Analysis (FEA)-based dynamic simulation technology is used to model stress, deformation, and performance characteristics of garments under movement, providing scientific quantitative data to support design optimization. The User Co-creation Module enables interaction between consumers and designers, allowing consumers to select styles, patterns, and colors to customize personalized sportswear. This co-creation model not only enhances consumer engagement but also provides brands with authentic market demand data, driving further development of customization and user-driven design.

2.3 System Architecture and Interaction Interface Design

The platform's system architecture adopts a modular and layered design, comprising the data layer, service layer, and front-end layer. The Data Layer is responsible for storing design materials, user information, and simulation models. Cloud-based storage ensures cross-platform data sharing, enabling designers and consumers to access data anytime and anywhere. The Service Layer facilitates the operation of core functional modules, such as inspiration generation, dynamic simulation, and design editing. Each module operates independently, ensuring the platform's flexibility and scalability. The Front-End Layer emphasizes user experience, featuring a clean and efficient interaction interface. The design interface adopts a modular layout, allowing users to perform complex design tasks through drag-and-drop and click operations. The virtual try-on interface offers multi-angle views, enabling users to rotate and zoom in on 3D models for detailed observations of garments. The platform also supports multi-language switching and cross-device operation, enhancing user convenience and satisfaction. The interaction interface planning focuses on the combination of functionality and intuitiveness. For instance, in the dynamic try-on module, users can not only view garment performance in various scenarios but also adjust parameters such as fabric flexibility or pattern density through the interface, observing changes in real time. Similarly, the inspiration generation module is designed for ease of use, where users can select style tags or upload materials to receive recommended design solutions. This intelligent recommendation mechanism reduces creative obstacles and boosts design efficiency. The system architecture and interaction interface of the platform achieve a balance between advanced technology and user experience, providing a powerful and user-friendly comprehensive design environment for both designers and consumers. By addressing the unique requirements and trends of sportswear design, the platform significantly enhances design efficiency and promotes the deep integration of digital technology into the sportswear industry.

3. Technical Implementation and Development Process

The digital transformation of sportswear design requires a robust framework of technical implementation and development processes. This begins with modular design methods, progresses through the development of core algorithms, and culminates in system integration and optimization. Each step plays a vital role in ensuring the platform's success. Below, these aspects are detailed.

3.1 Rapid Development of Sportswear Based on Modular Design

Modular design serves as the foundation for the rapid development of sportswear. This approach divides garment design into multiple functional modules, with each module being independent and reusable. Sportswear typically comprises components such as the body, sleeves, collars, and waist decorations, each of which may vary depending on the requirements of different sports scenarios. The first step in modular design is to meticulously define these components and assign adjustable parameters to each module. For example, collar modules can be designed in various shapes (e.g., stand collars, round collars, V-necks), while sleeve modules may include options for short sleeves, long sleeves, or sleeveless designs. These variations can be achieved through parametric modeling. The flexibility of modular design lies at its core. By defining module parameters, designers can adjust individual components, such as changing the length of sleeves or altering the shape of the body, without needing to redesign the entire garment.

This significantly reduces redundant work while greatly enhancing design efficiency. Furthermore, all modules are stored in a cloud-based database that contains 3D models, material information, adjustable parameters, and historical records. This ensures traceability and rapid retrieval of design modules. Another critical step in modular design is the seamless assembly and optimization of modules. Designers use real-time rendering tools in three-dimensional space to combine individual modules into a complete garment design. Assembly algorithms ensure smooth connections between modules, guaranteeing that the final design meets both aesthetic and functional requirements. For instance, during the assembly process, the system automatically detects the boundary conditions of each module and adjusts them to prevent inconsistencies in size or shape. The effects of module assembly are illustrated in Figure 4.

Figure 4: Illustration of Module Assembly Effects

The implementation of modular design relies heavily on parametric modeling techniques. Parametric modeling enables designers to generate diverse design styles by adjusting a few parameters. For example, adjusting the waist circumference parameter can create garments of various sizes, while altering the collar width can produce different collar styles. This approach significantly enhances the flexibility and scalability of the design process.

3.2 Core Algorithms and Functional Implementation

Building on modular design, the platform requires robust core algorithms to support diverse design needs and performance optimization. The three most critical components are 3D modeling and rendering, dynamic simulation, and functional realization. 3D modeling serves as the foundation for sportswear design. The platform employs a triangle mesh generation algorithm based on computer graphics to create geometric models of garments. These models are rendered using Physically Based Rendering (PBR) technology, which enhances the realism of materials by accurately simulating gloss, texture, and lighting effects. For instance, when designing a running jacket with reflective stripes, PBR technology can precisely replicate how light interacts with the reflective material, producing highly realistic visuals. Examples of different fabric textures are shown in Figure 5.

Figure 5: Illustration of Various Fabric Textures

Dynamic simulation is used to evaluate the performance of sportswear in real-world scenarios. For example, when an athlete is running or jumping, the stretching, compression, and friction properties of the garment need to be rigorously tested and optimized. Dynamic simulation is achieved through Finite Element Analysis (FEA), allowing designers to input material properties and motion conditions into the platform. The system then calculates stress distribution, deformation, and comfort levels in real-time. These simulation results provide quantitative data for optimizing design details, such as adjusting fabric elasticity or reinforcing seams. The 3D display of these results is depicted in Figure 6.

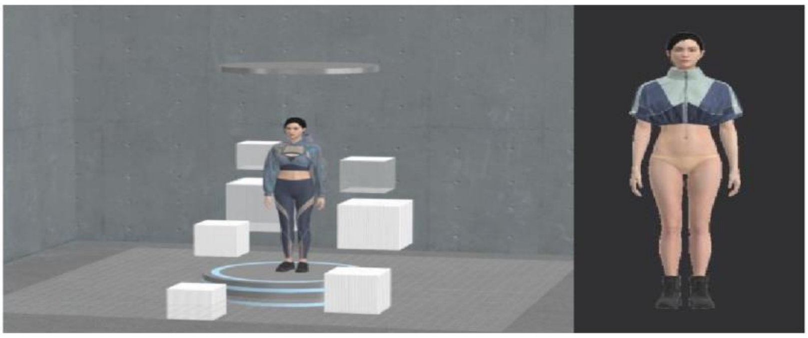

Figure 6: 3D Display of Garment Performance

3.3 System Integration and Optimization

The platform's system architecture is modular and layered, consisting of three main components: the data layer, service layer, and front-end layer. The Data Layer manages all design-related data, including 3D garment models, material properties, user preferences, and dynamic simulation results. Cloud-based storage enables cross-platform data sharing, ensuring that designers and users can access information anytime and anywhere. The Service Layer acts as the system's core, integrating all functional modules such as inspiration generation, design editing, dynamic simulation, and user co-creation. Each module operates as an independent microservice, enhancing the system's stability and enabling future feature expansions. For instance, if a new dynamic simulation algorithm is required, it can be added as a standalone microservice without disrupting existing functionalities. The Front-End Layer serves as the user-facing component of the platform, focusing on delivering an intuitive and efficient user experience. The design interface employs a modular layout, enabling users to perform complex design tasks through drag-and-drop and simple click operations. For example, in the inspiration generation module, users can select preferred style tags, and the platform automatically recommends relevant design materials and elements. The virtual try-on interface offers multi-angle views, allowing users to rotate and zoom in on 3D models to inspect garment details closely. To enhance operational efficiency, the platform incorporates several performance optimization strategies. These include the use of multi-threading and GPU acceleration in dynamic simulation and real-time rendering, which significantly reduce computation times.

Additionally, 3D models and material data are compressed to minimize storage and transmission requirements. Caching techniques are also employed to avoid redundant calculations in inspiration recommendations and design previews, thereby improving response times. The ultimate goal of system integration is to achieve seamless collaboration among all modules. For instance, when a user adjusts a garment parameter in the virtual try-on interface, the platform instantly updates the 3D model and recalculates dynamic simulation data. All these processes occur in the background, ensuring a smooth and uninterrupted user experience. The sportswear design platform achieves a comprehensive digital design workflow, from inspiration generation to dynamic simulation, through modular design, core algorithm development, and system optimization. Modular design ensures flexibility and scalability, core algorithms support diverse design needs, and system integration enables efficient collaboration among functional modules. This technological framework not only enhances design efficiency but also leverages data-driven optimization to support the digital transformation of the sportswear industry. The platform's development meets current market demands and lays a solid foundation for future innovation and industry growth.

4. Experimental Validation

To evaluate the effectiveness of the VR-based sportswear design platform, a survey was conducted among 33 professional fashion designers. These participants, with extensive experience in garment design, were invited to use the platform to complete a range of tasks, including modular design, dynamic simulation, and virtual prototyping. Following their usage, the designers provided feedback through a detailed questionnaire. Their responses were analyzed to gain insights into the platform's usability, functionality, and areas for improvement.

4.1 User Feedback and Functional Testing Results

As shown in Table 1, the results from the survey indicated a largely positive reception of the platform across various dimensions. Designers were asked to rate their satisfaction with the platform's usability, modular design features, dynamic simulation capabilities, and its contribution to sustainable design.

Table 1: (a) Summary of Designer Feedback on the VR-Based Sportswear Design Platform

QUESTION	VERY POSITIVE	POSITIVE	NEUTRAL	NEGATIVE	VERY NEGATIVE
USABILITY SATISFACTION	13	16	4	0	0
INTERFACE INTUITIVENESS	15	12	6	0	0

Table 1: (b) Summary of Designer Feedback on the VR-Based Sportswear Design Platform

QUESTION	VERY POSITIVE	POSITIVE	NEUTRAL	NEGATIVE	VERY NEGATIVE
MODULAR DESIGN EFFICIENCY	18	10	5	0	0
DYNAMIC SIMULATION EFFECTIVENESS	20	8	4	1	0
3D MODELING REALISM	17	12	4	0	0
SPEED AND RESPONSIVENESS	10	12	5	0	0
VIRTUAL TRY-ON HELPFULNESS	21	8	3	1	0
SUPPORTS SUSTAINABLE DESIGN	16	12	5	0	0

Regarding overall usability, a significant 88% of the designers expressed satisfaction, with many highlighting the platform's user-friendly interface as a key strength. Most participants described the interface as intuitive and easy to navigate, with 82% stating that the design tools were straightforward to use. This suggests that the platform effectively reduces the learning curve for professionals, enabling them to focus on the creative process. The modular design feature emerged as one of the most appreciated aspects of the platform. About 85% of the designers found this feature extremely or very helpful, emphasizing its role in enabling rapid prototyping and customization. The ability to modify and combine modules such as sleeves, collars, and body sections provided flexibility and efficiency, significantly accelerating the design process. The dynamic simulation feature was another highly rated functionality.

Over 85 percent of participants found it effective in visualizing fabric behavior during movement. This capability allowed designers to test the performance of their garments under conditions such as stretching, compression, and dynamic motion. Many participants remarked that the ability to simulate these factors virtually saved significant time and resources compared to traditional prototyping methods. Similarly, the 3D modeling and rendering capabilities of the platform received positive feedback, with 88% of designers rating the visual realism of the rendered garments as highly accurate. This level of realism enabled them to make more informed decisions regarding fabric selection, color schemes, and overall design aesthetics. The platform’s virtual try-on functionality also stood out as a key feature, with 88% of designers describing it as helpful or very helpful. The try-on tool provided a precise representation of how garments would fit and appear on different body types, enabling early-stage adjustments and reducing reliance on physical samples. This feature was particularly appreciated for its role in improving design accuracy and user confidence. In terms of sustainability, 85% of respondents agreed that the platform contributed to sustainable design by reducing material waste.

Designers acknowledged that the virtual prototyping approach eliminated the need for excessive fabric usage and minimized the production of physical prototypes. Many participants highlighted how this aligned with the growing emphasis on environmentally friendly practices in the fashion industry. However, some participants reported minor issues related to system responsiveness. Specifically, 15% experienced occasional delays when working with complex designs or rendering high-resolution visuals. While these instances did not significantly hinder the overall experience, they indicate a need for optimization to improve the platform's processing speed and reliability.

4.2 Data Analysis and Platform Improvement Directions

The analysis of the survey responses revealed several strengths of the platform, as well as opportunities for enhancement. The positive feedback highlights the platform's ability to address key challenges in sportswear design, while constructive criticism provides guidance for future improvements.

Enhanced Dynamic Simulation Precision: Although the dynamic simulation feature was widely praised, some designers suggested further refining its accuracy, especially for niche fabrics or extreme motion scenarios. Expanding the library of material properties and integrating more advanced simulation algorithms, such as finite element analysis (FEA), could improve its precision.

System Performance Optimization: Addressing the occasional delays reported by a subset of users is crucial for maintaining a seamless experience. Optimizing GPU usage, parallel processing, and memory management can enhance the platform's responsiveness, especially for high-complexity tasks.

Customizable Interface and Workflow: While the interface was generally rated as intuitive, some designers expressed a desire for greater customization options. Allowing users to tailor the layout and tools to their specific workflows could improve usability and productivity. Features such as drag-and-drop modules, customizable toolbars, and user-defined presets would further enhance the user experience.

Expanded Sustainability Metrics: Building on its success in reducing material waste, the platform could introduce additional features to track sustainability metrics. These might include monitoring carbon footprints, energy savings, and waste reduction for each design iteration. Such tools would provide designers with a comprehensive understanding of the environmental impact of their work.

The validation study demonstrated the platform's effectiveness in addressing the needs of professional fashion designers. Its strengths lie in its intuitive usability, modular design efficiency, realistic 3D modeling, dynamic simulation precision, and contribution to sustainable design practices. However, targeted improvements in system performance, dynamic simulation accuracy, interface customization, and sustainability metrics would further enhance its functionality and user satisfaction. These refinements will position the platform as a leading tool in the field of sportswear design, blending innovation, efficiency, and environmental responsibility.

5. Conclusion

The research and development of the VR-based sportswear design platform have demonstrated its significant potential to revolutionize the traditional design workflow in the fashion industry. This study successfully integrated modular design principles, dynamic simulation capabilities, and realistic 3D modeling within a user-friendly system, providing a comprehensive tool tailored to the specific needs of sportswear designers. The platform's modular design approach proved to be a cornerstone of its success, allowing designers to rapidly prototype and customize garments by manipulating interchangeable components. This flexibility not only streamlined the design process but also enhanced creativity and efficiency.

The dynamic simulation feature provided valuable insights into fabric behavior under various conditions, enabling designers to optimize garment functionality and performance virtually. Furthermore, the platform's 3D modeling and rendering capabilities achieved a high degree of realism, empowering designers to make more informed decisions regarding material choices and aesthetics. The experimental validation through feedback from 33 professional fashion designers further confirmed the platform's effectiveness. The majority of participants praised its usability, modular design efficiency, and sustainability features, emphasizing its role in reducing material waste and aligning with environmentally friendly practices.

Additionally, the virtual try-on functionality was highlighted as a critical tool for enhancing design accuracy and reducing reliance on physical samples. However, the study also identified areas for improvement, including refining the precision of dynamic simulations, optimizing system performance for complex tasks, and introducing greater interface customization options. These enhancements will further solidify the platform's value as a transformative tool in sportswear design. This research highlights the platform's ability to address key challenges in the sportswear design process, offering a seamless integration of advanced technologies to enhance efficiency, creativity, and sustainability. With targeted refinements, the platform is poised to become a leading solution for the digital transformation of the fashion industry, paving the way for innovative and sustainable design practices.

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