

Garment fit assessment: A comprehensive literature review integrating fabric mechanics, 3D simulation, and machine learning techniques

Phan Ha Nhu Ngoc^{1,2}, Bui Mai Huong¹, Le Song Thanh Quynh^{1,*}



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¹Department of Textile and Garment Engineering, Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), VNU-HCM, Ho Chi Minh City, Vietnam

²Faculty of Garment Technology - Fashion, Industrial University of Ho Chi Minh City (IUH), Ho Chi Minh City, Vietnam

Correspondence

Le Song Thanh Quynh, Department of Textile and Garment Engineering, Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), VNU-HCM, Ho Chi Minh City, Vietnam

Email: lstquynh@hcmut.edu.vn

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ABSTRACT

Garment fit is a key factor influencing consumer comfort, confidence, and purchasing decisions, particularly in the context of e-commerce, where the inability to try on products physically results in poor fit being a leading cause of costly product returns, material waste, and customer dissatisfaction. These challenges negatively impact not only consumer experience but also operational efficiency and environmental sustainability. However, traditional methods for evaluating garment fit are subjective, time-consuming, and inconsistent, highlighting the urgent need for more accurate, objective, data-driven, and scalable assessment solutions. This study presents a systematic literature review of research on garment fit assessments published between 2017 and 2025. The review emphasizes integrated approaches that combine fabric mechanical analysis, three-dimensional (3D) virtual simulation, and machine learning techniques to enhance the precision and efficiency of fit evaluation processes. A range of methodologies is examined and categorized into four major research areas: (1) 3D simulation and virtual try-on technologies; (2) data-driven machine learning and analytics; (3) material fabric-body interaction analysis; and (4) hybrid multi-technology integration frameworks. Results indicate that advanced tools such as 3D body scanning, simulation-based pattern adjustment, and predictive machine learning models have emerged as dominant technologies in recent studies. The review also identifies research gaps, such as a lack of standardized data formats, limited realism in fabric and body modeling, and poor interpretability of AI-driven systems. To address these limitations, the study proposes future research directions, including the development of open-access datasets, improvements in simulation fidelity, and enhancements in model explainability. Ultimately, these insights aim to inform the development of next-generation garment fit assessment frameworks that are accurate, transparent, personalized, and adaptable for practical use in the evolving digital fashion landscape.

Key words: Garment fit, material mechanical properties, 3D Simulation, machine learning, fashion industry

INTRODUCTION

In the dynamic e-commerce environment, the inability to physically try on apparel has made sizing inconsistencies a leading cause of returns, significantly increasing operational costs and harming the reputations of fashion brands. Research^{1,2} indicate that these sizing issues result in return rates of 30% to 40% in the online fashion industry, causing billions of dollars in annual losses and exacerbating environmental impacts due to increased transportation-related carbon emissions. The fit of a garment, encompassing the correlation between body dimensions and garment size, as well as shape, comfort, and aesthetics, is crucial for the apparel supply chain, benefiting numerous stakeholders, including consumers, designers, and producers, throughout the product development process³⁻⁶.

Traditional garment fit assessment methods are significantly reliant on subjective determinations made by designers and manufacturers, resulting in inconsistencies and biases⁷. This method requires the manufacture of several expensive physical samples, hindering design replication and evaluation, particularly in e-commerce. The issue escalates because of the variety of consumer body forms and the intricate qualities of textiles⁵. Researchers and manufacturers are exploring innovative technical solutions to overcome these limitations. The integration of 3D body scanning delivers accurate body measurements through simulation technology^{8,9}. The examination of fabric mechanical properties improves precision by simulating authentic garment-body interactions^{10,11}. Moreover, machine learning methods facilitate the analysis of huge datasets, predictive modeling, and automated design modifications^{12,13}. The integration of

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these technologies substantially reduces expenses, accelerates product development, and enhances the precision of fit evaluation.

Although the potential of modern technologies such as 3D simulation, fabric mechanical analysis, and machine learning has been recognized, their effective integration into the garment fit assessment process remains a significant challenge for academia and industry. This paper analyzes representative works (2017–2025) to synthesize approaches, identify methodologies, evaluate pros/cons, pinpoint research gaps, and propose future directions. It provides a comprehensive overview to help experts build effective solutions for the fashion industry’s digital transformation. The paper is structured as follows: Section 2 presents the research methodology, Section 3 summarizes and analyzes typical works, Section 4 discusses the findings, trends, problems, and future study areas, while Section 5 summarizes the insights and implications for both academic research and industrial applications.

RESEARCH METHODOLOGY

This study employed a systematic literature review to collect and synthesize research on integrating fabric mechanical parameters, 3D simulation, and machine learning in garment fit assessment. The process consisted of four steps: keyword identification, database selection (e.g., Google Scholar, ScienceDirect, IEEE Xplore), data extraction using a review matrix, and result analysis. The methodology is represented in Figure 1.

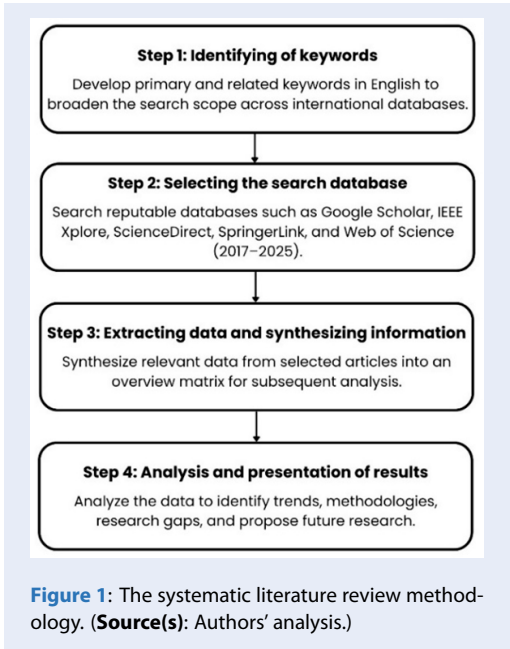
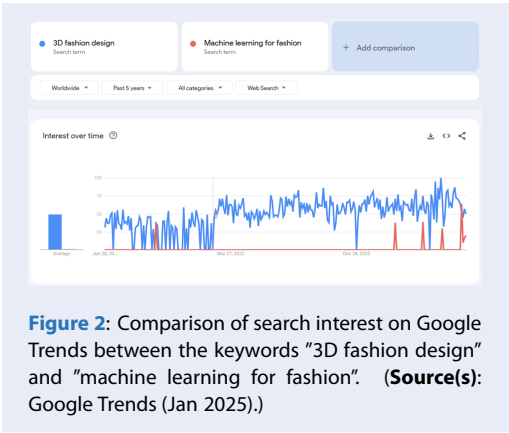


Figure 2 shows that over the past five years, Google Trends data reveal significantly greater global interest in “3D fashion design” than in “machine learning for fashion”. This highlights the adoption and benefits of 3D design, including cost efficiency, rapid prototyping, enhanced creativity, and user experience. Although less prominent, “machine learning for fashion” is showing growth due to its potential in trend prediction, production optimization, and personalization. Google Scholar data (Table 1) indicate that both fields share a similar academic interest, suggesting a growing convergence in fashion research.



Moreover, publication trends on ScienceDirect (Table 2) confirm a comparable and sustained research focus on both “3D fashion design” and “machine learning for fashion”. Specifically, general search queries return approximately 77,815 results for “3D fashion design” and 62,151 results for “machine learning for fashion”. These results not only illustrate growing academic interest but also reflect a shift from manual fit evaluation toward data-driven and digitalized approaches. The dominance of machine learning and body scanning studies suggests a prioritization of automation and personalization, aligning with the apparel industry’s shift toward virtual prototyping and intelligent design.

These findings reinforce the convergence of digital design technologies and AI-driven approaches as critical pillars in contemporary garment-fit research and innovation.

Table 1: Statistics of search results for the keywords “3D fashion design” and “machine learning for fashion” on Google Scholar.

Time Range	3D fashion design	Machine learning for fashion
General	Approximately 1,440,000 results (0.05 seconds)	Approximately 1,390,000 results (0.09 seconds)
10 years	Approximately 307,000 results (0.07 seconds)	Approximately 253,000 results (0.08 seconds)
5 years	Approximately 97,500 results (0.07 seconds)	Approximately 112,500 results (0.05 seconds)

Source(s): Google Scholar (Jan 2025).

Table 3: Summary of primary research based on four categories for evaluating garment fit.

No	Methodology	Garment fit’s viewpoints	Specific Methods	Key References	Limitations
1	3D Simulation, Body Scanning, and Virtual Reality	Customers, Designers, Manufacturers	CLO3D, Optitex, Lectra Modaris, VR, 3D/4D scanning, Pressure maps, Dynamic anthropometry	4,14–31	Limited accuracy in fabric simulations and soft tissue deformation; minimal automation in landmark identification and fit optimization; restricted generalizability across various garments and user groups.
2	Material Properties and Fabric–Body Interaction	Customers, Manufacturers	Kawabata Evaluation System, FAST systems, PicoPress sensors, Dynamic anthropometry, Pressure measurement	32–35	Challenges in modeling nonlinear, anisotropic fabric properties persist; subjective evaluations prevail, and methods vary across studies, making it difficult to accurately simulate the dynamics of fabric-body interactions.
3	Machine Learning and Data Analytics	Customers, Designers, Manufacturers	ANN, Decision Trees, Regression, CNN, Random Forest, SVM, PCA, GAN, Naive Bayes, K-means	36–47	Limited diversity in datasets, inadequate integration of fabric mechanics, low interpretability of complex models, and subjective evaluations of comfort and aesthetics are often neglected.
4	Integrated Multi-Technology Approaches	Customers, Designers, Manufacturers	ANN, GAN, BP-ANNs, PCA, AHP, CLO3D simulation, Sensor systems	5,8,48–58	Data incompatibility, complex integration and synchronization challenges, inadequate quantitative measures for subjective comfort and aesthetics, high technical requirements, and obstacles to practical deployment.

Source(s): Authors’ analysis.

Table 2: Statistics of search results for the keywords “3D fashion design” and “Machine learning for fashion” on ScienceDirect.

Time Range	3D fashion design	Machine learning for fashion
General	77,815 results	62,151 results
10 years	49,360 results	40,596 results
5 years	31,099 results	29,225 results

Source(s): ScienceDirect (Jan 2025).

**SYNTHESIS AND ANALYSIS OF
PRIMARY APPROACHES TO
GARMENT FIT ASSESSMENT**

Table 3 summarizes the literature review on garment fit assessment and classifies current approaches into four main groups: (1) 3D simulation, body scanning, and virtual reality; (2) machine learning and data analytics; (3) material properties and fabric–body interaction; and (4) multi-technology integration. The objectives are to identify the research status, analyze mainstream methodologies, clarify previous strengths and weaknesses, and identify research gaps to guide future development.

Perspectives on Garment Fit Assessment

Garment fit can be interpreted from multiple perspectives, reflecting the distinct objectives of consumers, designers, and manufacturers^{3–5}. From the consumer’s viewpoint, fit is primarily perceived through qualitative and subjective factors such as comfort, ease of movement, and visual appearance, which strongly influence purchase satisfaction and return rates^{41,51}. These perceptions are shaped by psychological and contextual factors, making them difficult to standardize. In contrast, designers and manufacturers emphasize quantitative and objective assessments that associate garment performance with body measurements and the mechanical properties of fabric^{10,11,16,31,44–47}. This perspective enables pattern adjustment, sizing-system calibration, and material optimization based on measurable parameters^{16,31}. Establishing a conceptual link between subjective and objective perspectives is crucial for advancing garment-fit research. This understanding lays the groundwork for developing data-driven and simulation-based approaches that translate conceptual insights into practical fit evaluation methods^{8,13,48–50,58}.

**Classification of Garment Fit Assessment
based on Application Techniques**

Building upon the conceptual perspectives discussed above, a garment-fit assessment method has been developed through several major technical approaches that integrate body, fabric, and design data in different ways (Table 3).

3D simulation, body scanning, and virtual reality

3D simulation technology has become a key tool in visual garment fit evaluation, utilizing platforms such as CLO3D, Optitex, and Lectra Modaris. Studies^{14–17} have shown that pressure, deformation, and drape maps from simulations help designers adjust patterns and identify areas of discomfort. Other works^{18–20} highlight the effect of body movement on fabric deformation, particularly in sportswear and protective gear. Research using 3D/4D body scanning^{21–25} has enabled greater personalization and real-time motion simulation. Among these, CLO3D offers realistic visualization and flexible fabric data integration for research, while Optitex is better suited for industrial pattern workflows. Their complementary strengths highlight the balance between simulation accuracy and production efficiency. Despite these advancements, challenges persist in simulating nonlinear fabric mechanics, bridging the gaps between virtual and experimental results^{4,26–29}, and modeling the deformation of soft tissue^{30,31}. Future efforts should focus on standardizing simulation methods, enhancing the quality of scan data, and developing more realistic body models.

Material Properties and Fabric–Body Interaction

The mechanical characteristics of the fabric and the interaction between the fabric and the body are essential for precise fit modeling. Research^{32–35} has utilized tools such as the Kawabata Evaluation System (KES) and the Fabric Assurance by Simple Testing (FAST) system to simulate parameters like stretch, drape, and friction. Recent studies³⁵ have also examined fabric pressure to enhance comfort and shaping. Dynamic elements, such as posture and mobility, significantly influence garment behavior³⁵. Integrating these empirical measurements with calibrated digital simulations enhances consistency between virtual and physical results, reduces the need for repeated sampling, and improves predictive reliability. However, the nonlinear and anisotropic properties of fabrics continue to challenge the reproducibility of simulation outcomes.

Machine Learning and Data Analysis

Machine learning is increasingly applied to evaluate garment fit because of its ability to process complex datasets from scanning, simulation, and user feedback. While some studies^{36–39} have employed models such as neural networks and decision trees to predict fit, others^{40–43} have incorporated anthropometric and psychographic data for personalized sizing. In addition, studies^{44–47} combine 3D simulation with deep learning to automate drape visualization and size selection. Decision Tree-based algorithms (e.g., J48, Random Forest) provide transparent rule extraction, which helps interpret influential parameters, whereas Neural Network-based models (e.g., ANN, CNN, GAN) achieve higher predictive accuracy but have limited explainability. Hybrid approaches can balance these aspects for practical application. However, limited and similar datasets^{39,42,46}, insufficient modeling of fabric mechanics^{41,43}, and the lack of quantification of subjective comfort remain persistent issues. Additionally, the complexity of high-dimensional models can hinder their adoption in industry.

Integrated multi-technology approaches

Recent research is increasingly integrating 3D simulation, experimental fabric data, sensor inputs, and machine learning to achieve more accurate fit assessments^{5,8}. For instance, pressure and humidity sensors validate virtual try-on results^{49,51} and ANN or GAN frameworks enable real-time pattern optimization^{48,53,57,58}. However, interoperability among data sources and computational complexity remain major barriers. Effective frameworks should therefore prioritize data standardization and modular integration to enhance reproducibility and scalability.

DISCUSSION

The Current Status And Emerging Trends In Fit Assessment Research

An overview of major research from 2017 to 2025 reveals that the assessment of garment fit has shifted progressively from traditional empirical evaluations to integrated, data-driven digital solutions. Three key technological pillars—fabric mechanical analysis, 3D virtual simulation, and machine-learning-based data analytics—jointly enable the transition from manual evaluation to predictive and automated fit assessment. As illustrated in Figure 3, machine learning, body scanning, and virtual try-on emerge as the most dominant methods, reflecting the field's growing emphasis on automation, personalization, and sustainable digital product development.

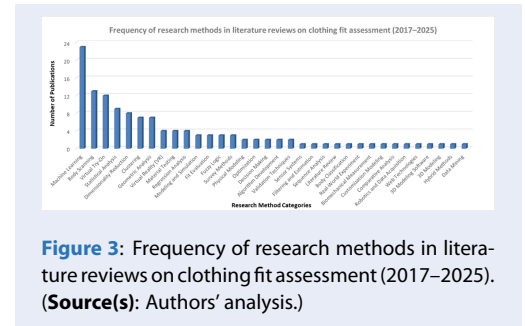


Figure 3: Frequency of research methods in literature reviews on clothing fit assessment (2017–2025). (Source(s): Authors' analysis.)

Current Research Limitations and Future Directions

Although extensive research has been conducted on garment-fit assessment, particularly integrating fabric mechanics, 3D simulation, and machine learning, several critical challenges remain to enhance accuracy and industrial applicability.

A key challenge is the lack of standardization in input data. Each research direction exhibits particular strengths but also inconsistencies in data structure and acquisition. For instance, 3D body-scanning approaches generate highly realistic human models, yet they produce personalized and costly datasets that are difficult to generalize. In contrast, fabric-based approaches provide measurable mechanical parameters but often lack unified datasets that describe material characteristics. These inconsistencies limit the model's reproducibility and interoperability. Therefore, developing standardized datasets that integrate both body geometry and fabric mechanical information—supported by machine-learning techniques—could accelerate prediction, improve accuracy, and enhance interpretability, thereby bridging virtual simulations with manufacturing practice.

Another persistent limitation concerns the realism of simulations and evaluation standards. Integrating physical fabric parameters, body-scan geometry, and user perception remains incomplete. Limited and inconsistently formatted datasets complicate analysis, while most simulations are static and fail to reflect deformation during motion. Moreover, the absence of quantitative and universally accepted indicators for virtual-fit evaluation leads to a reliance on expert or sensory judgment, which restricts comparability and industrial adoption.

Furthermore, machine-learning models face constraints related to interpretability and data quality. Deep neural networks often achieve high predictive performance but act as “black boxes” that require large volumes of reliable data, which is seldom available to small or medium-sized enterprises. Hence,

future studies should emphasize explainable, data-efficient, and user-friendly models that can be seamlessly integrated into digital design workflows.

Proposing potential future research directions

The challenges identified in the field of integrated fit assessment underscore the need for more comprehensive and targeted research efforts. To address current limitations and improve applicability in the fashion industry, several key directions are proposed:

- First, developing reliable machine learning and simulation systems requires standardized, open datasets. These should include fabric properties, 3D body scans, simulation outputs, and user feedback. Open-access and standardized data can improve prediction reliability and reduce e-commerce return rates by ensuring more consistent virtual try-on results.
- Next, enhancing material modeling and 3D avatars is essential. Models must better reflect nonlinear, dynamic fabric behavior, while efficient reconstruction of the wearer's body data will improve accuracy in virtual fitting. Accurate digital prototypes can reduce the number of physical samples and minimize production waste.
- Finally, improving the interpretability of machine learning models is crucial. Integrating explainable AI frameworks will support transparent and data-driven design adjustments, while establishing quantitative metrics for both technical and comfort factors will enable consistent evaluation across research and production environments.

CONCLUSION

In the current sustainable fashion industry, garment fit is a key factor that affects comfort during wear and influences customers' purchasing decisions. Developing a process to evaluate garment fit before mass production helps reduce time spent on physical sample editing and limits fabric usage in the prototyping phase. However, this research direction still faces challenges, particularly in data standardization, accurate fabric and body modeling, a lack of objective evaluation criteria from 3D simulation, and limited interpretability of machine learning models. These issues highlight the urgency to invest further in research and development to achieve comprehensive, practical, and scalable solutions.

The analysis of current limitations clarifies technical issues and reveals weaknesses in data collection, technology integration, and standardization in assessment. This provides an essential basis for propos-

ing relevant research directions and building a reliable fit assessment system that is easy to implement and compatible with production conditions. At the same time, these solutions must align with sustainability goals, including resource optimization, waste reduction, and support for on-demand fashion models. By explicitly linking these directions to industrial challenges—such as reducing return rates, minimizing sampling waste, and improving transparency in digital workflows—the proposed approaches strengthen both the practical and sustainable relevance of garment-fit assessment. Integrating virtual fitting, machine learning, and simulation technologies into the supply chain helps reduce costs and supports both green growth and personalization in the fashion industry.

LIST OF ABBREVIATIONS

- 3D – Three-dimensional
- 4D – Four-dimensional (including time or motion)
- AHP – Analytic Hierarchy Process
- AI – Artificial Intelligence
- ANN – Artificial Neural Network
- CAD – Computer-Aided Design
- CNN – Convolutional Neural Network
- CLO3D – CLO3D garment simulation and virtual try-on software
- FAST – Fabric Assurance by Simple Testing
- GAN – Generative Adversarial Network
- IEEE – Institute of Electrical and Electronics Engineers
- KES – Kawabata Evaluation System
- ML – Machine Learning
- PCA – Principal Component Analysis
- SVM – Support Vector Machine
- VR – Virtual Reality

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CONFLICT OF INTEREST

There is no conflict of interest.

AUTHORS' CONTRIBUTION

Nhu Ngoc Phan Ha: Conducted the literature review, synthesized findings, and wrote the main manuscript. Huong Mai Bui: Supervised the research process, revised the manuscript for submission.

Song Thanh Quynh Le: Supervised the research process, revised, and finalized the manuscript for submission.

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Đánh giá độ vừa vặn của trang phục: Tổng quan nghiên cứu tích hợp cơ học vải, mô phỏng 3D và học máy

Phan Hà Như Ngọc^{1,2}, Bùi Mai Hương¹, Lê Song Thanh Quỳnh^{1,*}



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¹Bộ môn Kỹ thuật Dệt May, Khoa Cơ khí, Trường Đại học Bách khoa TP. Hồ Chí Minh (HCMUT), Đại học Quốc gia TP. Hồ Chí Minh (VNU-HCM), TP. Hồ Chí Minh, Việt Nam

²Khoa Công nghệ May – Thời trang, Trường Đại học Công nghiệp TP. Hồ Chí Minh (IUH), TP. Hồ Chí Minh, Việt Nam

Liên hệ

Lê Song Thanh Quỳnh, Bộ môn Kỹ thuật Dệt May, Khoa Cơ khí, Trường Đại học Bách khoa TP. Hồ Chí Minh (HCMUT), Đại học Quốc gia TP. Hồ Chí Minh (VNU-HCM), TP. Hồ Chí Minh, Việt Nam

Email: lstquynh@hcmut.edu.vn

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TÓM TẮT

Độ vừa vặn trang phục là yếu tố then chốt ảnh hưởng đến sự thoải mái, sự tự tin và quyết định mua sắm của người tiêu dùng, đặc biệt trong thương mại điện tử, nơi việc không thể thử đồ trực tiếp khiến tình trạng không vừa vặn trở thành nguyên nhân phổ biến dẫn đến hoàn trả sản phẩm, lãng phí vật liệu và giảm mức độ hài lòng. Những vấn đề này không chỉ làm giảm trải nghiệm khách hàng mà còn ảnh hưởng đến hiệu quả vận hành và tính bền vững môi trường. Tuy nhiên, các phương pháp đánh giá độ vừa vặn truyền thống thường mang tính chủ quan, thiếu nhất quán và tốn thời gian, cho thấy nhu cầu cấp thiết về các giải pháp đánh giá chính xác, khách quan, dựa trên dữ liệu và có khả năng mở rộng. Nghiên cứu này thực hiện tổng quan tài liệu có hệ thống về các nghiên cứu đánh giá độ vừa vặn trang phục được công bố trong giai đoạn 2017–2025, tập trung vào các cách tiếp cận tích hợp kết hợp phân tích cơ học vải, mô phỏng ảo ba chiều (3D) và kỹ thuật học máy nhằm nâng cao độ chính xác và hiệu quả đánh giá. Các phương pháp được phân loại thành bốn hướng nghiên cứu chính gồm: (1) mô phỏng 3D và công nghệ thử đồ ảo; (2) học máy và phân tích dựa trên dữ liệu; (3) phân tích tương tác giữa vải và cơ thể; và (4) khung tích hợp đa công nghệ. Kết quả cho thấy quét cơ thể 3D, điều chỉnh rập dựa trên mô phỏng và các mô hình học máy dự đoán đang giữ vai trò chủ đạo. Đồng thời, tổng quan cũng chỉ ra các hạn chế như thiếu chuẩn dữ liệu, mức độ chân thực còn hạn chế trong mô hình hóa vải và cơ thể, cũng như khả năng diễn giải thấp của các hệ thống AI, từ đó đề xuất các hướng nghiên cứu tương lai nhằm phát triển khung đánh giá độ vừa vặn thể hệ mới chính xác, minh bạch, cá nhân hóa và phù hợp với bối cảnh thời trang số.

Từ khóa: Độ vừa vặn trang phục, tính chất cơ học vật liệu, mô phỏng 3D, học máy, ngành thời trang

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