Optical Strain Measurement of Textile Materials Using AI-Assisted Instrumentation for Smart Apparel Systems

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Abstract. AI-based optical measurement technology is increasingly being used to analyze textile mechanics, while modular fashion offers a sustainable approach through multifunctional garment design. However, the mechanical behavior of deformable modular garments remains underexplored. This study aims to determine how strain and deformation are distributed in a modular patchwork denim jacket during body movement and transformation into a tote bag, and to assess how effectively an AI-based optical measurement system can analyze this mechanical behavior. An AI-assisted optical measurement approach was used to evaluate the strain distribution and deformation behavior in a deformable modular denim garment during movement and transformation. The findings indicate that high strain concentrations primarily occur in the shoulder, elbow, and lateral torso regions during the folding and panel rearrangement stages. The patchwork zone consisting of thicker denim exhibits lower deformation and higher stiffness, while flexible sections enhance movement adaptability. The results demonstrate that AI-assisted image processing successfully identifies displacement patterns and produces real-time strain visualization with high accuracy. Furthermore, the modular construction redistributes mechanical stress across multiple zones of the garment, reducing local strain

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accumulation and enhancing structural stability during repeated transformation cycles.

1 Introduction

The advancement of smart textiles, wearable technology, and artificial intelligence (AI) has transformed the fashion industry toward adaptive and multifunctional apparel systems [1]. In this context, modular fashion has emerged as an innovative approach that enables garments to adapt to different user needs through transformable structures and multifunctional configurations. A modular product is made up of independent modules with interfaces, and its overall function is achieved by assembling these modules through their interfaces [2]. Patchwork denim garments, particularly those developed from recycled materials, offer significant potential for sustainable and adaptive fashion applications due to their structural durability, modular composition, and material reusability.

Recent developments in smart textile engineering have demonstrated the growing importance of optical sensing, AI-assisted strain analysis, and wearable instrumentation systems for evaluating textile deformation and mechanical behaviour. Algorithms can analyse extensive datasets and simulate numerous design variations to identify the most effective configurations, drastically speeding up the development process. AI also enables adaptive MOs that can dynamically adjust to changing imaging conditions, improving performance in real-time [3]. The use of AI can seamlessly integrate interface personalisation and multimodal input into fashion design and recommendations. By leveraging user preferences, body measurements, and style preferences, artificial intelligence (AI) systems can provide highly personalised fashion recommendations. The integration of multiple input modalities, including text, images, and sketches, allows designers and users to easily communicate their design ideas [4]. Libanori et al. (2022) highlighted that smart textiles integrated with sensing technologies can support adaptive wearable systems capable of monitoring movement, flexibility, and user interaction [5]. Similarly, Phan et al. (2022) reported that adaptive textile structures with flexible mechanical properties improve garment responsiveness and movement adaptability in wearable applications [6]. These studies indicate that textile mechanics and intelligent sensing systems are becoming essential components in future smart fashion engineering.

Optical strain measurement methods such as Digital Image Correlation (DIC) enable non-contact evaluation of fabric deformation through image-based displacement tracking. Meng et al. (2022) demonstrated that optical strain mapping systems combined with DIC provide accurate full-field strain visualization for material deformation analysis [7]. Furthermore, Yang et al. (2021) proposed Deep Learning-Based Digital Image Correlation methods capable of improving displacement and strain measurement accuracy through AI-assisted image processing [8]. These technologies allow automatic detection of strain concentration areas, deformation patterns, and movement responses in real time.

In wearable textile applications, AI-based sensing systems have also been utilised for motion recognition and adaptive garment analysis. Xu et al. (2022) developed wearable textile pressure sensor arrays for human activity recognition [9], while Tai et al. (2022) investigated wearable biaxial strain sensors integrated into textile structures for flexible deformation monitoring [10]. Moreover, Truong et al. (2022) emphasized the importance of fabric-based wearable sensors for intelligent apparel systems capable of responding dynamically to user movement [11]. However, despite the rapid development of smart textile sensing technologies, research integrating AI-based optical measurement systems with modular transformable fashion products remains limited.

This study aims to determine how strain and deformation are distributed in a modular patchwork denim jacket during body movement and transformation into a tote bag, and to assess how effectively an AI-based optical measurement system can analyze this mechanical behavior. An AI-assisted optical measurement approach was used to evaluate the strain distribution and deformation behavior in a deformable modular denim garment during movement and transformation. The research employs an AI-based optical measurement system consisting of a high-resolution camera, controlled lighting environment, motion tracking markers, and AI-assisted image processing algorithms to analyse textile mechanics during movement and garment transformation stages.

The novelty of this research lies in the interdisciplinary integration of AI optical sensing, textile mechanics, adaptive modular fashion design, and sustainable denim patchwork construction. Unlike conventional fashion studies that focus primarily on aesthetics, this research combines engineering-based strain analysis with multifunctional garment transformation systems. The findings are expected to contribute to the development of intelligent, sustainable, and physics-informed fashion engineering for future wearable technology and smart textile applications.

2 Method

This study employed an experimental research approach integrating artificial intelligence (AI), optical instrumentation, and textile mechanics analysis to investigate strain distribution and deformation behaviour in a multifunctional modular patchwork denim jacket capable of transforming into a tote bag. The research workflow consisted of garment development, optical measurement setup, experimental testing, AI-based image processing, and strain analysis.

2.1 Design and Material Preparation

The experimental garment was designed as a multifunctional modular patchwork denim jacket constructed from recycled denim fabrics with different thicknesses, textures, and elasticity properties. The garment incorporated detachable and transformable components, allowing the jacket to be converted into a tote bag through folding and panel rearrangement mechanisms. (See figure 1).

Fig. 1. Modular adaptive product design and bag

Patchwork assembly techniques were applied to create segmented structural zones with varying mechanical responses during movement and transformation processes. Different denim orientations and stitching configurations were intentionally arranged to investigate their influence on strain distribution and deformation behaviour. Previous studies reported that heterogeneous textile structures significantly influence fabric flexibility [12], strain concentration, and adaptive wearable performance in smart textile systems [13].

2.2 Optical Measurement System

An AI-based optical measurement system was utilized to capture textile strain and deformation behaviour [14]. Hild & Roux explain that DIC is a non-contact optical technique for measuring displacement and strain through digital image analysis of material surfaces. The experimental setup consisted of: a high-resolution digital camera system, Controlled lighting environment, Motion tracking markers on the textile surface, AI-assisted image processing software, and Optical strain analysis algorithm [15].

The optical system continuously recorded fabric deformation during various body movements and garment transformation stages, including arm flexion, torso rotation, dynamic stretching, folding, and tote bag conversion processes. Digital image sequences were captured to analyse full-field strain distribution patterns across different garment zones [14]. Optical strain analysis in this research adopted Digital Image Correlation (DIC)-based methods, which have been widely applied for non-contact displacement and strain measurements in textile engineering and smart material analysis. Meng et al. (2022) demonstrated that optical strain mapping integrated with DIC enables accurate visualization of material deformation under dynamic loading conditions. In addition, Yang et al. (2021) proposed AI-assisted Deep DIC methods that improve displacement tracking and strain calculation accuracy through deep learning image processing approaches [8].

2.3 Experimental Procedure

The jacket was tested under controlled movement simulations involving repetitive motion cycles and garment transformation activities. Motion tracking markers were positioned on selected patchwork regions, including the shoulder, elbow, torso, side panels, and modular connection areas. The experimental procedure consisted of three testing stages: 1) Static Condition Analysis, the garment was analysed in its initial jacket configuration without movement to identify baseline structural conditions; 2) Dynamic Movement Analysis, the wearer performed repetitive body movements such as arm lifting, torso rotation, and stretching to evaluate deformation behaviour under dynamic mechanical loading. Previous wearable sensing studies showed that movement-related textile deformation strongly affects ergonomic performance and strain distribution in adaptive garments; and 3) Transformation Analysis, the jacket-to-tote-bag transformation process was recorded continuously to analyse displacement, strain concentration, and structural response during folding and modular rearrangement stages. The modular transformation mechanism allowed observation of localized deformation zones and stress redistribution during structural reconfiguration.

2.4 AI-Based Image Processing and Strain Analysis

Captured image sequences were processed using AI-assisted image analysis and Digital Image Correlation (DIC) techniques to detect displacement fields and strain distribution patterns. The AI system automatically identified motion trajectories, deformation regions, and localized strain concentrations in real time. The strain analysis focused on tensile deformation behaviour, fabric displacement patterns, maximum strain concentration zones, structural stability of modular components, and flexibility and adaptive movement response.

2.5 Data Interpretation

The obtained strain and displacement data were interpreted using principles of textile mechanics and material physics. Mechanical interactions between tensile force, fabric elasticity, stitching configuration, and modular construction were analysed to evaluate garment adaptability and structural efficiency. The results were further assessed to determine the effectiveness of AI-integrated optical instrumentation for adaptive wearable systems and sustainable modular fashion applications. The integration of recycled denim materials and intelligent optical sensing reflects current developments in sustainable smart textiles and adaptive wearable engineering.

3 Results and Discussions

The experimental results demonstrated that the AI-based optical measurement system successfully identified textile strain distribution and deformation behaviour in the multifunctional modular patchwork denim jacket during both body movement and jacket-to-tote-bag transformation processes. The integration of high-resolution optical imaging, motion tracking markers, and AI-assisted Digital Image Correlation (DIC) enabled accurate real-time visualization of displacement patterns and strain concentration zones across the garment structure.

3.1 Strain Distribution During Body Movement

Optical analysis revealed that the highest strain concentrations occurred in high-mobility regions, particularly the shoulder, elbow, and lateral torso areas. These regions experienced significant fabric displacement during arm flexion, torso rotation, and dynamic stretching movements. The strain maps generated through AI-assisted image processing showed non-uniform deformation patterns caused by variations in fabric orientation, patchwork assembly, and stitching configuration. The shoulder region exhibited the largest tensile deformation due to repeated upward arm movement, while the elbow zones showed localised strain accumulation caused by continuous bending motion. Similar findings were reported by Xu et al. (2022), who identified movement-dependent strain variations in wearable textile sensor systems for human activity recognition. Furthermore, Meng et al. (2022) demonstrated that optical strain mapping, integrated with DIC, provides accurate full-field deformation visualisation of flexible materials and textile structures.

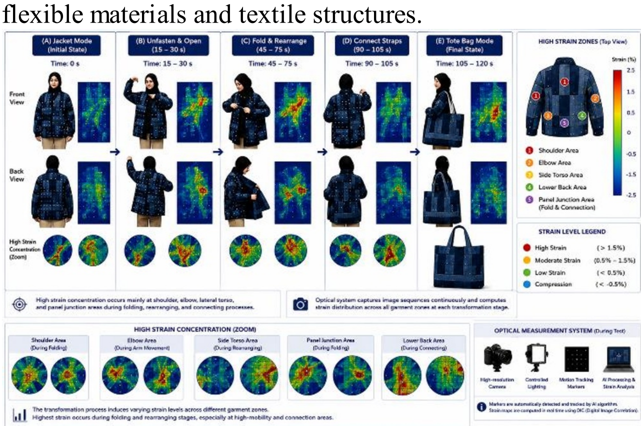

Fig. 3. Strain distribution during jacket to tote bag transformation based on AI.

Figure 3 focuses specifically on the Strain Distribution During Jacket to Tote Bag Transformation section. One human subject was involved in the experiment. The modular denim jacket prototype underwent two transformations: from jacket to tote bag and from tote bag back to jacket. Strain and deformation were recorded using an AI-based optical measurement system during the transformation process and body movement trials.

3.2 Optical Analysis During Jacket-to-Tote-Bag Transformation

During the transformation process from jacket to tote bag, optical measurements identified substantial displacement and strain changes in folding regions, modular joints, and detachable panel areas. High strain values were observed during panel rearrangement and folding stages, particularly along zipper lines, strap connections, and side seams. AI-assisted image processing successfully tracked fabric displacement trajectories throughout the transformation sequence and generated continuous strain heatmaps for each structural stage. The results showed that modular construction reduced stress accumulation by allowing localised deformation rather than uniform structural tension across the entire garment. This adaptive deformation behaviour contributed to improved flexibility and minimized mechanical resistance during transformation cycles as shown in figure 4.

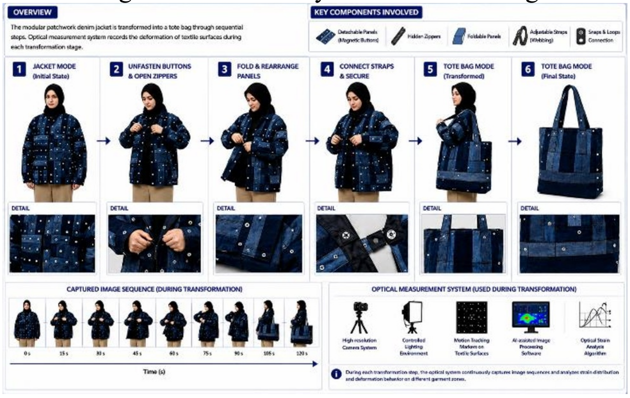

Fig. 4. Transformation Process from jacket to tote bag based on AI.

This image specifically displays the process of transforming a denim patchwork jacket into a tote bag, complete with the stages of folding, rearranging panels, connecting straps, and the integration of an optical measurement system to record the deformation of the textile during the shape change.

3.3 AI-Based Optical Measurement Performance

The AI-integrated optical system effectively improved the accuracy and efficiency of textile deformation analysis compared to conventional manual observation methods. AI-assisted DIC processing enabled automatic identification of displacement vectors, strain concentration zones, and motion trajectories with high spatial resolution. The generated heatmap visualisations provided quantitative strain measurements and detailed deformation mapping across different garment zones. Yang et al. (2021) similarly demonstrated that Deep Learning-Based DIC systems improve displacement and strain measurement precision through automated image analysis techniques.

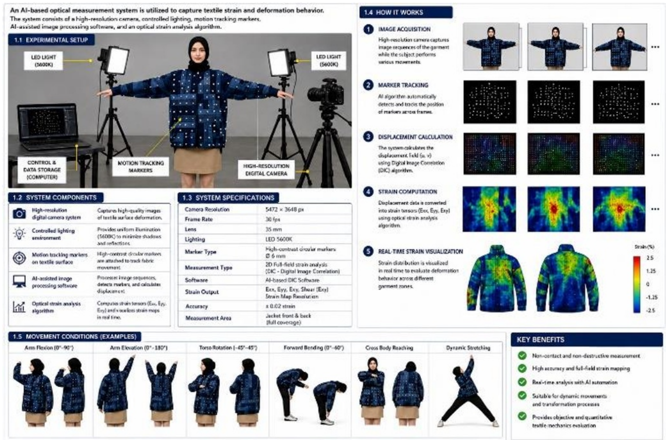

Fig. 5. Optic measurement system based on AI.

Figure 5 focuses specifically on the Optical Measurement System section, with a clearer visual of the experimental setup, system components, AI optical strain analysis workflow, equipment specifications, and body movement conditions used to measure textile deformation on a modular denim patchwork jacket.

3.4 Physics Interpretation of Textile Deformation

The modular patchwork construction exhibited varying mechanical responses depending on denim thickness, panel orientation, and seam configuration. Patchwork regions composed of thicker recycled denim layers showed lower deformation values and higher structural rigidity, whereas lighter and more flexible sections demonstrated greater adaptability to body movement. This behaviour indicates that heterogeneous textile composition significantly influences stress distribution and ergonomic performance in adaptive apparel systems. The segmented patchwork arrangement redistributed tensile forces across multiple structural zones, reducing excessive strain concentration in single garment areas. Tai et al. (2022) similarly reported that flexible textile structures with multi-directional strain response improve mechanical adaptability and deformation stability in wearable strain-sensing applications.

Fig. 6. Deformation Analysis (Folding stage) based on AI.

Figure 6 specifically clarifies the Deformation Analysis section, displaying the displacement field, 3D surface deformation, mesh overlay strain map, as well as quantitative data of fabric deformation at the folding stage of a denim patchwork jacket during the transformation process into a tote bag.

3.5 Implications for Smart and Sustainable Fashion Engineering

The integration of AI optical sensing, modular garment construction, and recycled denim materials demonstrates the potential for developing intelligent and sustainable adaptive apparel systems. The multifunctional jacket maintained its mechanical integrity during repetitive transformation cycles while providing flexible movement adaptability and ergonomic performance. The study also demonstrated that recycled denim patchwork maintained structural stability and performance despite undergoing repeated transformation cycles, highlighting its suitability for sustainable fashion applications. The findings contribute to the advancement of smart fashion engineering by combining textile physics, wearable sensing technologies, AI-assisted deformation analysis, and sustainable modular design approaches. This interdisciplinary integration supports future developments in intelligent wearable systems, adaptive textiles, and computational fashion engineering.

4 Conclusions

This study demonstrated the successful integration of artificial intelligence (AI)-based optical measurement systems with modular patchwork denim apparel for analysing textile strain and deformation behaviour in adaptive wearable systems. The AI-assisted optical instrumentation, combined with Digital Image Correlation (DIC), effectively captured real-time displacement patterns, strain distribution, and mechanical responses during body movement and jacket to tote bag transformation processes. The findings revealed that high strain concentrations primarily occurred in high-mobility regions such as the shoulder, elbow, and lateral torso areas. Variations in denim thickness, fabric orientation, and patchwork configuration significantly influenced deformation behaviour and stress distribution across the garment structure. Thicker denim panels exhibited higher rigidity and lower deformation, while flexible modular sections improved adaptability and ergonomic movement performance. The limitations of testing in this study is in a controlled lighting environment and briefly discuss how the AI-based optical measurement system might perform in dynamic, real-world lighting conditions. Overall, this research contributes to the development of smart fashion engineering through the interdisciplinary integration of textile physics, wearable sensing technology, AI-driven optical instrumentation, and sustainable modular design.

This publication was funded by the Indonesia Endowment Fund for Education (LPDP) on behalf of the Indonesian Ministry of Higher Education, Science and Technology, and managed under the EQUITY Program (Contract Number 4308/B3/DT.03.08/2025 and B/284/UN39/HK.07.00/2025).

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