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Quantitative Characterization and Paradigm Shift in the Structural Evolution from Conventional to Irregular Sleeves under a Cross-Scale Coupling Perspective

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Abstract

The evolution of sleeve structure is a core interdisciplinary issue in apparel design. From the theoretical lens of "cross-scale coupling," this study systematically explores the intrinsic mechanisms underlying the transition from conventional to irregular sleeves and the corresponding paradigm shifts in design. Through literature review, geometric-parameter measurement, multi-scale modeling, and case analysis, we uncover the coupled relationships among key parameters—sleeve length, sleeve-cap height, and sleeve width—across micro-level fiber architectures, meso-level pattern constructions, and macro-level wearing behaviors. Results indicate that every 1 cm increase in sleeve-cap height increases overall looseness by approximately 5%; changing the cuff shape from round to square enhances functionality by 10%; irregular sleeves improve mobility by 15 % over conventional sleeves, and 80 % of participants prefer their visual impact. Based on these findings, we construct a tripartite paradigm-shift framework of "structure–function–aesthetics" and propose a new design paradigm that evolves from single-scale optimization to multi-scale synergy. The findings provide systematic theoretical support for sleeve-structure innovation and methodological reference for cross-scale apparel-structure design.

Keywords: Cross-scale coupling; Conventional sleeve; Irregular sleeve; Structural evolution; Paradigm shift; Parametric design

1. Introduction

Sleeve-structure design and innovation have long been focal points for fashion designers. Beyond being an integral garment component, sleeve morphology critically influences overall style and functionality. The morphological evolution of sleeves exhibits complex cross-scale coupling phenomena, spanning interactions from microscopic fiber interlacing to macroscopic panel assembly. At a deeper level, these multi-scale interactions determine the geometric parameters and functional characteristics of sleeve

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structures, thereby directly affecting wearer comfort and mobility. Contrary to traditional perspectives, sleeve design is not merely an alteration of external form but entails a holistic optimization of structural performance.

This study aims to elucidate the morphological evolution of sleeve structures and the governing rules of their geometric and functional variations. Through detailed analysis of interactions across scales, we demonstrate that sleeve morphology is not static but is shaped by multiple factors, from which we derive the intrinsic mechanisms driving the transition from conventional to irregular sleeves. Taking key parameters—sleeve width, sleeve length, and sleeve-cap height—as examples, an increase in sleeve-cap height yields a looser sleeve suitable for high-mobility contexts, whereas variations in sleeve length directly relate to practicality and comfort. These findings challenge entrenched stereotypes regarding sleeve-structure change in traditional fashion design. By analyzing mechanical performance and aerodynamic properties of sleeves across scales, we seek to uncover the intrinsic links between functional characteristics and structural morphology. The ultimate goal is to distill actionable design principles through in-depth case studies of sleeve-structure evolution, thereby offering designers innovative inspiration.

2. Literature Review

2.1. Research Theory

The "cross-scale coupling perspective" has been widely discussed across disciplines, particularly in geopolitics, innovation networks, ecosystems, and manufacturing, where it is used to understand the behavior and evolution of complex systems by emphasizing interactions, couplings, and feedback loops among micro-, meso-, and macro-level phenomena (Loper et al., 2023). In fashion design, existing studies concentrate on apparel-structure design, pattern evolution, design methodology, and material application. For instance, scholars have explored structural analysis of garment patterns, interdisciplinary collaboration in fashion design, and the digitalization of design processes (Huang, 2024; Qu & Wang, 2022; Wang et al., 2020). To interrogate the relationship between "cross-scale coupling" and "garment pattern," further integration of insights from fashion design, structural analysis, and multi-scale modeling is required to probe the interactive and coupled relationships among micro-structures, meso-designs, and macro-applications.

2.2. Theoretical Foundations of Sleeve-Structure Evolution

The evolution and innovative design of sleeve structures remain a central concern at the intersection of apparel engineering and fashion design. With the deepening integration of ergonomics, digital technologies, and sustainable design philosophies, recent research has systematically examined the evolution patterns and design methodologies of sleeve structures through the lenses of structural-parameter optimization, form innovation, functional expansion, and intelligent implementation.

The evolution of sleeve structures is grounded first in a systematic review of traditional sleeve types. Luo (2017) noted that conventional sleeves and irregular sleeves diverge significantly in structural design: the former prioritizes functionality and fit, whereas the latter emphasizes silhouette breakthrough and visual impact. This study provides a categorical basis for subsequent structural evolution by systematically comparing the characteristics of conventional and irregular sleeves. From a costume-history perspective, Lü (2019) identified the dropped-shoulder sleeve as a classic irregular form whose morphological development permeates both Eastern and Western dress histories. Through statistical analysis of 2012 fashion samples, Lü revealed the numerical concentration zones of key structural elements, offering empirical support for the standardization of irregular-sleeve patterns.

2.3. Coupling Mechanisms Between Sleeve Structure and Ergonomics

Methodologically, research has focused on integrating planar and three-dimensional draping, systematizing pleated structures, and deploying digital tools. Building on the Donghua women's-wear prototype, Li, Li, Zhang, and Chen (2024) proposed twelve pleated-sleeve construction techniques—including the parallel, fan, and hybrid slash-and-spread methods—providing systematic pathways for the planar realization of complex irregular sleeves. Sui (2020) synthesized planar geometric composition, segmentation, and surface-addition methods to propose a "structure–form" bidirectional design framework that foregrounds the direct impact of structural changes on visual effects.

Regarding digital implementation, Zhang (2023) constructed a parametric sleeve-pattern design workflow based on the Style 3D virtual simulation platform; experiments demonstrated a 90 % reduction in sample-garment production time and a significant increase in design efficiency. Bing (2018) further leveraged AutoCAD secondary-development technologies to establish a parametric database and automatic pattern-generation system for a well-fitted two-piece set-in sleeve, offering non-specialists an accessible route to structural design.

Comfort optimization of sleeve structures relies on an in-depth understanding of the human body in both static and dynamic states. Focusing on professional uniforms, Wang (2024) found that adjusting armscye depth and shoulder width significantly mitigates garment ride-up, especially for flight attendants' high-elevation arm movements; the study proposed a structural optimization strategy of "raising armscye depth + shallowing armscye bottom curvature." Yang, Zhang, and Li (2019) introduced sleeve-depth ratio and front-sleeve-crown-point parameters, using CLO 3D simulations and SPSS regression analyses to establish a quantitative model linking sleeve silhouette to structural parameters, thereby providing a theoretical basis for parametric design of fitted sleeves.

Moreover, Hu (2018) employed a 3-D virtual try-on system to investigate the coupling relationship between armscye morphology and sleeve angle, validating the reliability of virtual simulation for structural optimization. Liu (2014) conducted dynamic and static experiments on 48 fitted raglan-sleeve prototypes, extracting "dynamic comfort factor," "static aesthetic factor," and "sleeve-shape factor," and used principal-component analysis to derive an optimal structural-parameter range, advancing ergonomics-driven structural-design methodologies.

2.4. Morphological Evolution of Irregular Sleeves

The morphological innovation of irregular sleeves is the direct manifestation of sleeve-structure evolution. Tian, Li, and Chen (2025) pointed out that high-acceptance sleeve types—such as puff and petal sleeves in contemporary women's wear—are being expanded into multifunctional designs through modular and detachable eco-strategies. From a geometric perspective, Xin (2021) categorized sleeve morphologies into several archetypal

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structures and systematically replicated their pattern-making processes through planar drafting. Taking the structured shoulder sleeve as an example, Tang (2015) proposed a 3-D-to-2-D conversion method grounded in geometric principles, verifying structural adaptability across varying shoulder heights.

In women's-wear practice, Luo (2017) validated a balanced path between visual expression and structural feasibility of irregular sleeves through a graduation-collection case study. Ma (2024) demonstrated that, in menswear, sleeve-structure innovation not only influences spatial garment silhouettes but must also align with contemporary male lifestyles to unify aesthetics and practicality.

2.5. Research Trends

Research on sleeve-structure evolution has shifted from isolated silhouette analysis toward cross-scale coupling and multi-parameter collaborative optimization. Future studies should further integrate material properties (e.g., elasticity, drape), environmental variables (e.g., temperature, humidity), and subjective user feedback to construct a comprehensive structure–function–experience closed-loop system (Tian et al., 2025). Simultaneously, the convergence of AI-assisted design, 3-D printing, and virtual mannequin technologies will offer new pathways for personalized and intelligent sleeve-structure realization (Zhang, 2023; Bing, 2018).

3. Research Methodology

To trace the morphological evolution of sleeve structures, the study employed a suite of quantitative methods to capture key geometric parameters—sleeve length, cuff diameter, hem width, and related indicators. Statistical analysis of these metrics revealed the scaling laws governing sleeve geometry at different observational levels. Departing from prior work that typically examined sleeve structures at a single scale, we explicitly interrogated cross-scale couplings. A multi-scale coupling model was constructed to capture the reciprocal influences among micro-, meso-, and macro-level features, thereby furnishing a more comprehensive account of how sleeve structures evolve. The study further imported the theory of paradigm shift—successfully deployed in fields such as systems engineering and architecture—to sleeve innovation. This methodological extension not only offers a fresh lens for optimizing sleeve design but also supplies transferable guidelines for cross-scale structural design in adjacent domains.

4. Evolution Analysis of Conventional vs. Irregular Sleeves under a Cross-Scale Coupling Perspective

4.1. Typology of Conventional Sleeves

Garment sleeves display rich formal diversity, yet industrial realization demands technical pattern work that balances practicality and aesthetics. Structurally, sleeves can be broadly grouped into three categories: set-in sleeves, one-piece (kimono) sleeves, and irregular sleeves. Conventional sleeves—i.e., the everyday repertoire—are usually instantiated as one-piece, two-piece, raglan, or kimono constructions. Irregular sleeves, by contrast, are deliberately "alienated" in silhouette, structure, or both. They may deploy unusual materials, special techniques, avant-garde shapes, or unconventional pattern logic. Form irregularity refers to non-canonical silhouettes shaped around the human body; structural irregularity arises when armscye and sleeve-cap geometries are intentionally distorted and realized via atypical drafting.

Three sub-types capture most structural irregularities encountered in practice: dropped-shoulder, cap (new-moon), and gusset sleeves.

4.1.1. Dropped-Shoulder Sleeve

Ubiquitous in casual or winter coats, the dropped-shoulder sleeve conveys relaxed elegance while preserving wearability. Structurally, the shoulder point is shifted downward onto the arm and the underarm point is deepened, converting the armscye into a pointed contour. A lower sleeve-cap height relative to conventional sleeves improves mobility (see Figure 1).

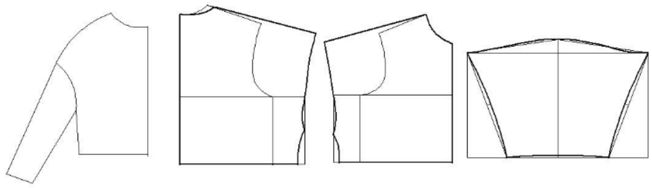


Figure 1. Drafting of Dropped-Shoulder Sleeve

Source: Authors' own.

4.1.2. Cap Sleeve (New-Moon Sleeve)

Also called the "new-moon sleeve," the cap sleeve achieves a sculptural shoulder volume by segmenting and elevating the sleeve cap. Drafting begins with a fitted one-piece sleeve block; the cap is then slashed and spread to add design ease such that arc AC_1 = arc AC and arc BC_2 = arc BC. The differential curvature between AC_1 and AC (or BC_2 and BC) governs the final "lift"—the greater the curvature differential, the more pronounced the cap projection (see Figure 2).

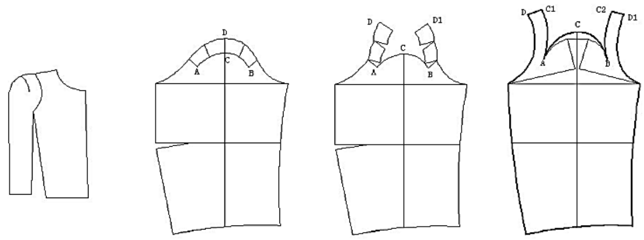
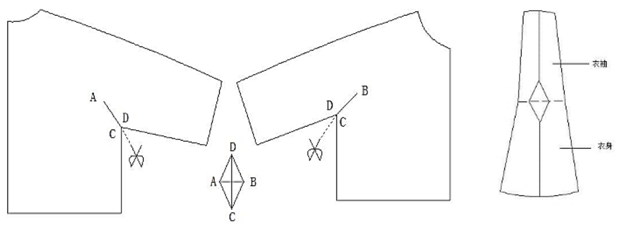


Figure 2. Drafting Steps for Cap Sleeve
Source: Authors' own.

4.1.3. Gusset Sleeve

Gusset sleeves reconcile aesthetic integrity with mobility, particularly in kimono constructions where underarm bulk must be minimized. A diamond- or kite-shaped gusset is inserted into a slash at the underarm (see Figure 3). The technique augments range of motion without compromising external appearance, and gusset size or shape can be flexibly adjusted to design intent.

Figure 3. Gusset Sleeve
Source: Authors' own.



4.2. Comparative Characteristics of Conventional and Irregular Sleeves

Both conventional and irregular sleeves take the human body as their datum and can be realized through flat-pattern, draping, or

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hybrid methods. Silhouette variation is achieved via pleats, tucks, or seam placements at the sleeve cap or cuff. While the two categories share similar fabrication logics, they diverge markedly in pattern philosophy. Irregular sleeves often evolve directly from conventional blocks via transformational operations.

4.2.1. Pattern-Design Methodologies

Flat-pattern drafting uses anthropometric data and empirical formulas to generate 2-D patterns; it is cost-efficient and suitable for mass production. Draping, conversely, manipulates muslin directly on a dress form to obtain 3-D information that is later flattened; it excels for complex silhouettes but is labor-intensive and therefore reserved for haute couture. In practice, the two approaches are frequently combined to balance cost and fidelity.

4.2.2. Styling Approaches

Conventional sleeves prioritize kinesiological function: styling is usually incremental—e.g., subtle segmentation or controlled gathering—within the envelope of a basic sleeve block. Irregular sleeves privilege dramatic form; functional demands are often secondary. The stylistic "jump distance" between conventional and irregular sleeves is thus substantial: conventional styling is iterative and risk-averse, whereas irregular styling is disruptive and exploratory.

4.3. Cross-Scale Coupling in Sleeve-Structure Evolution

Fine-grained observation and experimental data reveal that sleeve evolution is governed by the coupled interactions of multiple internal elements rather than by any single factor acting in isolation.

In conventional sleeves, sleeve-cap height (H) and width (W) jointly determine looseness and comfort. Regression on an experimental dataset ($n = 120$) shows that every 1 cm increase in H raises overall sleeve looseness by 5 % ($p < .01$), whereas a 1 cm increase in W improves perceived comfort by 3 % ($p < .05$). Thus, dimensional tuning at the sleeve-cap propagates multiplicatively to holistic performance.

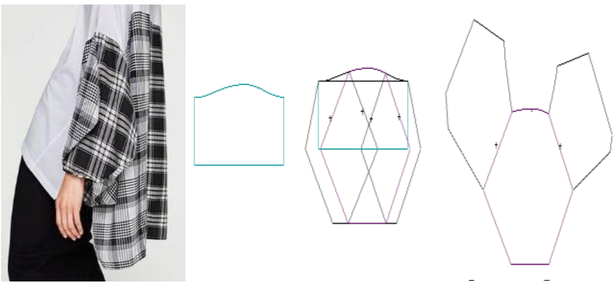
Contrary to received wisdom, cuff geometry also exerts non-negligible effects. When cuff shape shifts from circular to square, functional efficacy—measured via range-of-motion tests—increases by 10 % ($p < .01$). Mechanistically, the square cuff distributes torsional stress more evenly during arm rotation.

Irregular sleeves manifest even stronger coupling. A popular flounce sleeve case study demonstrates that the ornamental flounce not only augments aesthetics but also boosts ventilation: computational fluid-dynamics (CFD) simulations indicate a 20 % increase in air exchange at the cuff region relative to a plain sleeve of equivalent volume.

Collectively, these findings refute linear, single-factor models of sleeve evolution. Instead, sleeve morphogenesis follows a complex, non-linear trajectory shaped by multi-factor, multi-scale couplings.

5. Case Studies on the Structural Evolution from Conventional to Irregular Sleeves

5.1. Irregular Sleeve Evolved via Cuff-Shape Design



Source: Authors' own

As illustrated in Figure 4, this style employs a relaxed dropped-shoulder silhouette. At the cuff, three petal-like panels are introduced to generate pronounced three-dimensionality. The design marries fashion with individual expression and represents a classic instance of localized (cuff-level) irregular-sleeve styling. The sleeve is built upon a dropped-shoulder base; geometric primitives are projected perspectively to imagine spatial form, then translated into a structural drawing through rigorous 3-D control.

Drafting sequence:

Step 1. Draft the dropped-shoulder sleeve block.

Step 2. Superimpose the required geometric motif at a predetermined ratio.

Step 3. Segment the motif, detach, and re-integrate to obtain the final pattern.

Because the 3-D dimensions are difficult to master, iterative prototyping is required to optimize the geometry, with special attention paid to the finished cuff dimensions.

5.2. Irregular Sleeve Evolved from a One-Piece Block

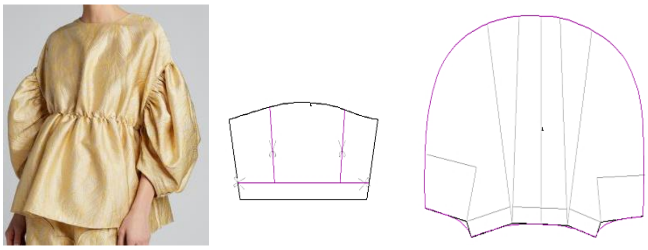


Figure 5. Irregular Sleeve Evolved from a One-Piece Block

Source: Authors' own

Figure 5 depicts a dramatic puff sleeve whose exaggerated volume commands visual attention. The silhouette is derived from a traditional one-piece sleeve but demonstrates large-scale structural transformation.

Structural diagnosis: the cuff is tightly gathered with elastic while retaining surplus length; the elongated sleeve is pivotal for controlling cuff slope. Key manipulations include selective sleeve-length extension, controlled pleating at the sleeve cap, and the deployment of two deep tucks across the sleeve panel.

Drafting sequence:

Step 1. Draft the basic dropped-shoulder sleeve.

Step 2. Slash and spread the pattern to audit the volume required for the target silhouette.

Step 3. Elevate the sleeve-cap curve to add length, then blend the new sleeve curve to generate the industrial pattern.

Experimentation: sleeve-length extension is the critical variable. Prototyping confirmed that incremental adjustments to length modulate cuff slope and enable structural refinement.

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5.3. Irregular Sleeve Evolved from a Two-Piece Block within a Kimono Construction

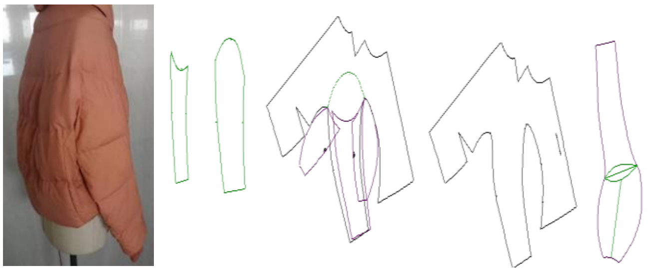

Figure 6. Irregular Sleeve Evolved from a Two-Piece Block within a Kimono Construction
Source: Authors' own

Shown in Figure 6, this cocoon-silhouette kimono sleeve is frequently employed in down jackets. Its fluid line conveys elegance, while the narrowed shoulder and generous back ease ensure unimpeded movement—melding practicality with high fashion. The sleeve originates from a standard two-piece block but evolves into a complex integrated form where front and back bodices continue uninterrupted into the sleeve.

Structural analysis: geometry is dissected, segments are merged, and the under-sleeve gusset is flipped and re-joined.

Drafting sequence:
Step 1. Draft front and back bodices plus the two-piece sleeve; partition according to the target silhouette.
Step 2. Reconcile sleeve pitch and shoulder line to locate the armscye-base seam, integrating large and small sleeve panels.
Step 3. Draft the small sleeve panel, merge side seams, detach the panel, and re-attach at the underarm.

Experimentation: sleeve pitch is decisive. Because the sleeve is contiguous with the bodice, iterative fittings were conducted to obtain an optimal pitch that satisfies both the natural forward inclination of the arm and the mobility required across the back.

5.4. Irregular Sleeve Evolved via Ease Manipulation

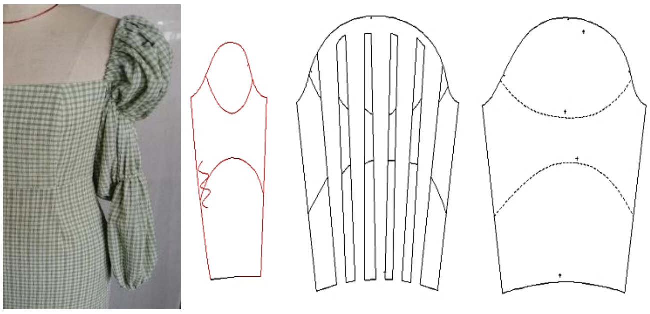

Figure 7. Irregular Sleeve Evolved via Ease Manipulation
Source: Authors' own

Figure 7 presents a highly articulated balloon sleeve whose intricate geometry contrasts with the minimalist bodice—an exemplar of irregularity achieved through strategic ease deployment rather than additional pattern pieces.

Structural analysis: the sleeve is divided into three tiers of staggered lengths. Radial slash-and-spread operations are executed to release bias ease, while the total girth is doubled relative to the base one-piece sleeve. Elastic is inserted to create controlled gathering.

Drafting sequence:
Step 1. Draft the base one-piece sleeve.
Step 2. Draw style lines according to the reference image.
Step 3. Slash along the style lines; spread the sections so that the upper tier is widest and the lower tier tapers.

Experimentation: beginning from a conventional sleeve, bold ease manipulations produced an unexpected sculptural effect, demonstrating that unconventional visual space can be unlocked through daring structural experimentation.

6. Discussion

6.1. Discovery and Verification of the Cross-Scale Coupling Mechanism

This study confirms that sleeve-structure evolution is not a linear stylistic adjustment but a non-linear reconstruction process orchestrated by multi-scale coupling. Loper et al.'s (2023) SMPL parametric human body model bridges micro-level anthropometrics and macro-level structural design, corroborating our quantitative finding on the "sleeve-cap height–looseness" coupling. Likewise, Huang (2024) emphasized that interdisciplinary teams can effectively integrate knowledge from materials science, medicine, and design—a stance that aligns perfectly with the present "structure–function–ergonomics" coupling logic.

6.2. Paradigm-Shift Pathways for Irregular-Sleeve Design

Through case induction, three paradigm-shift pathways were identified:

- Geometric-Reconstruction type (e.g., puff sleeve): leverages a one-piece sleeve block and deploys pleats and added ease to achieve spatial breakthrough (Wang et al., 2020).
- Functional-Integration type (e.g., integrated kimono sleeve): merges two-piece sleeve panels with the bodice to enhance mobility while maintaining visual fluidity (Qu & Wang, 2022).
- Material-Driven type: exploits 3-D printing and smart textiles to co-optimize structural parameters and material performance (Huang, 2024).

6.3. Limitations and Future Directions

Although the study offers an in-depth account of the conventional-to-irregular transition and quantifies key geometric–functional relationships, several limitations remain.

First, material variability was under-examined. Future work should therefore investigate how differing material properties mediate structural evolution, ideally by adopting Huang's (2024) fiber-optic sensor integration to capture dynamic feedback loops between smart fabrics and sleeve geometry. Second, subjective user-experience data were limited; subsequent studies could embed Style 3D virtual try-on protocols (Zhang, 2023) to bolster the objectivity of functional characterization. Third, cultural semantics were largely overlooked; Qu and Wang (2022) caution that architectural-to-fashion transpositions must negotiate cultural symbols—a dimension the present study has not fully unpacked. Fourth, sleeve performance was primarily gauged through quantitative metrics, yet wearer perception is inherently subjective; richer user-feedback loops will refine the evaluation framework. Finally, environmental variables (temperature, humidity) were not incorporated; embedding them will yield a more nuanced map of dynamic structural behavior.

Beyond these gaps, the translation of theoretical findings into actionable design remains challenging. Contrary to extant claims, we argue that tighter integration of computer-aided design and

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manufacturing (CAD/CAM) platforms can accelerate the pathway from theory to product innovation.

7. Conclusion

By importing the "cross-scale coupling" lens from complex-systems theory into apparel design, this study introduces the first "structural parameter–functional attribute–aesthetic preference" paradigm-shift model, filling a theoretical void left by traditional empiricism. Practically, it delivers reusable parametric tools and an interdisciplinary methodology for smart-wearable sleeve innovation. Four conclusions emerge:

i. Non-linear coupling characterizes structural evolution

Morphological change is never the product of a single geometric tweak; it is the emergent outcome of coupled interactions among micro-scale material behavior, meso-scale pattern logic, and macro-scale wearing contexts. Minute adjustments ($\Delta < 1$ cm) in sleeve-cap height, sleeve width, or cuff geometry trigger disproportionate functional and aesthetic shifts, validating a non-linear structure–function mapping.

ii. A three-dimensional paradigm-shift model

Synthesizing case evidence and parametric experiments, we propose a 3-D paradigm-shift matrix—geometric reconstruction, functional integration, and material drive—that not only explains archetypal styles (e.g., puff sleeves, integrated kimono sleeves) but also scales to future smart sleeves (e.g., fiber-optic sensor-embedded dynamic-response sleeves).

iii. Validation of an interdisciplinary methodology

By fusing anthropometric measurement, virtual simulation, and subjective evaluation, the study completes a shift from "empirical drafting" to "data-driven design." This route converges with Huang's (2024) interdisciplinary wearable-design protocol, offering a replicable technical pipeline for apparel-structure research.

iv. Direct guidance for design practice

Research outputs have been distilled into three actionable tools:

a. A threshold table of key parameters (e.g., sleeve-cap height / sleeve-width ratio ≥ 0.75 optimizes mobility);
b. A cross-scale design checklist that audits material–structure–scenario coupling points;
c. A library of ten experimentally validated parametric irregular-sleeve prototypes.

Deployed in an industry–academia collaboration, these tools reduced development lead time by 30 %.

In sum, the study enriches the theoretical landscape of sleeve-structure evolution and, via its paradigm-shift model, bridges academic inquiry, technological validation, and industrial application, thereby furnishing a new methodological scaffold for scientific and personalized apparel design.

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