Developing shape change-based fashion prototyping strategies

Citation for published version:
Huang, X, Kettley, S & Lycouris, S 2024, 'Developing shape change-based fashion prototyping strategies: Enhancing computational thinking in fashion practice and creativity', *Fashion Practice*, pp. 1-29. https://doi.org/10.1080/17569370.2024.2335615

Digital Object Identifier (DOI):
10.1080/17569370.2024.2335615

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Fashion Practice

Developing Shape Change-Based Fashion Prototyping Strategies: Enhancing Computational Thinking in Fashion Practice and Creativity

Huang, Xinyi, Kettley, Sarah and Lycouris, Sophia

Emerging technologies enable fluid and versatile material forms of fashionable wearables and e-textiles, with experts in engineering and material science proposing numerous strategies for dynamic textile and garment structures to satisfy various needs. Nevertheless, a critical gap remains in developing practical fashion prototyping strategies that fuse with computational thinking to challenge current norms and envision the future of fashion. This study introduces shape change-based fashion prototyping as a design strategy for dynamic expressions and affordances to inspire fashion practitioners' interdisciplinary endeavors. We present three studio-based practices as case studies to demonstrate how shape-changing mechanisms including servo motors, shape memory alloys, and pneumatics, spur new fashion construction skills and broaden the scope of potential applications. By doing so, this study contributes to material and conceptual innovation, creating pathways for the seamless integration of technologies from conceptualization, and implementation to envision. Our findings shed light on design possibilities and challenges and offer design recommendations that guide future endeavors. The implications of our research underscore the importance of adopting a relational approach to design variables, emphasize the value of fostering shared vocabulary between fashion and technical design, and highlight the transformative potential of shape-changing prototyping in reshaping the intricate body-material relationship.

Keywords: prototyping strategies, fashion and textile design, computational thinking, material movement, creativity

Introduction

Nowadays, academic interest in smart textiles and wearable technology has been growing, particularly in the exploration of shape-changing materials that respond to environmental or human-related stimuli through sensing and actuation technologies (Kontovourkis, Phocas, and Tryfonos 2013). Although current research on shape-changing wearables mostly centers on human-computer interaction and material science, there is an emerging need to incorporate a fashion and tailoring perspective. This comprehensive approach can help designers holistically consider how these wearables align with the body shape, occupy physical space, and lead to a more engaging fashion future (Freire et al. 2018). By integrating shape-changing mechanisms and fashion prototyping, designers can expand dynamic design vocabularies, pushing the boundaries of textile manipulation, pattern-cutting, and creative draping. This paper targets traditional fashion designers venturing into wearable tech. We developed shape change-based design strategies for fashion prototyping to bridge the gap between traditional fashion design practices and technological innovation, enabling the establishment of a shared communication language in interdisciplinary design (van Zilt et al. 2022). We present our research-through-design practice as case studies, showcasing knowledge generated through iterative crafting and making, which adapt to new situations, enabling self-expression, and cultivating skills and material understanding (Yair, Tomes, and Press 1999). We perceive this process as a path to self-mastery, where distinct fashion design skills are honed to interpret the evolving forms and contours, consequently guiding novel approaches to shaping techniques (Townsend and Mills 2013). Through detailed design analysis, we extract creative attributes encompassing both conceptual and material dimensions at each phase. Consequently, we provide design recommendations to inspire forthcoming research endeavors.

Literature review

Introducing Shape-Changing Mechanisms into Fashion Design

Material deformation systems employ various technical mechanisms like motors, shape memory alloys, and soft robotics to alter materials in orientation, form, spatiality, and texture. These alterations lead to diverse kinetic parameters, including changes in velocity, path, and direction. Furthermore, they can impart expressive qualities to the material, such as anthropomorphism and perceived softness (Rasmussen et al. 2012). Compared to conventional garments, shape-changing fashion offers numerous benefits. Its adaptable shapes and patterns can be customized in real-time, catering to the wearer's needs and preferences. This allows for a broad spectrum of self-expression and fulfills various functional needs (Rasmussen et al. 2012). Additionally, interactive technologies facilitate the programming of temporal structures, merging physical crafting with intellectual computation. This integration enables a tangible interaction with expressive material qualities (Vallgårda et al. 2017). Such interactions respond to the wearer's physical requirements and offer an immersive sensory experience, thereby promoting emotional sustainability through a deeper connection between the wearer and the garment (Huang et al. 2023).

This study incorporates three distinct shape-changing technologies, namely servo motors, shape memory alloys (SMAs), and pneumatics, into fashion prototyping. This approach aims to cultivate problem-solving skills and foster design thinking as a way of knowing (Bequette and Bequette 2012). The selection of these technologies is based on their comprehensive skill coverage, established use in fashion, potential for creative exploration, and feasibility for practical implementation.

Servo motors have found application in wearable fashion for altering silhouettes. Their actuation capabilities facilitate fabric manipulation through pulling and twisting, providing a versatile range of adjustable parameters such as rotation speed, angle, and acceleration. For instance, Genç et al. (2018) employed servo motors to transform the neck area of a dress into a flat poncho-like shape, making it adaptable to different occasions. Similarly, in the Moving Skirt project, servo motors located near the ankles in the skirt control its drape by winding threads connected to specific folds. This creates deliberate, dynamic movements in the skirt, enhancing the dancer's performance, seamlessly blending natural sway with programmed patterns (Toeters and Feijs 2014). However, our study transcends the conventional use of servo motors for gathering and shifting fabric surfaces. Instead, it reconsiders the spatiality and rhythms emerging from changes in fabric shape. The objective is to foster fluidity, ambiguity, and versatility in pattern cutting and overall aesthetics.

Given that servo motors are noticeable devices that take up physical space, we considered their strategic placement in our prototypes. However, the bulkiness and stiffness inherent in servo motors, present certain limitations. In contrast, Shape Memory Alloys (SMAs), which are wire-like materials with the ability to regain a predetermined shape after being deformed, offer a more lightweight and flexible solution. Nabil et al. (2019) skillfully infused fabrics with SMAs using sewing techniques. This approach grants fabrics self-morphing capabilities to display precise deformation and convey messages. Additionally, when SMAs are thoughtfully patterned around the body, they can generate purposeful force and torque. For example, Kim et al.(2020) applied SMA actuators into trousers, enhancing ankle movement through a unique structure with anchor points and wire routing. In this study, we explore the artistic and skillful integration of SMAs with traditional smocking techniques, yielding diverse shape-changing patterns and behaviors. Additionally, we integrate the inherent shape-changing principles of SMAs with zero-waste cutting methods, enhancing both the aesthetic and sustainable dimensions of our exploration.

In contrast to the shape memory capacity of SMAs, pneumatic structures have the ability to alter their shape by inflation and deflation. Such innovative designs, like the wing-like pneumatic bladders designed by Tsaknaki (2021), offer both visual and tactile sensations, creating affective experiences for the wearer. This interplay between temporal material qualities and human perception is a key area of exploration (Dassen and Bruns Alonso 2017). To facilitate the seamless integration of aesthetic expression in fashion, Perovich, Mothersill, and Farah (2013) combined pneumatics with origami patterns. This combination allows garments to strategically alter their shape in both length and width through precise folding mechanisms. In our study, our emphasis extends beyond dynamic interaction with material forms. We thoroughly consider production feasibility and technical structures. Additionally, we prioritize understanding and responding to the sensations experienced by the wearer. (Lee and Jirousek 2015). Our goal is to investigate viable approaches for on-body experimentation with pneumatic fashion prototypes, ensuring that our designs are innovative, wearable, and personalized.

Parallel Synergies: Computational Thinking and Fashion Design Approaches

In our research, we go beyond the material design layer of shape-changing fashion by integrating digital materials into wearables' design, form, and finish at a system and service level to develop holistic design solutions (Andersen et al. 2019). This involves the application of computational thinking, employing technical mechanisms, programming, and algorithmic thinking for problem-solving, pattern identification, stepwise solution development, and logical data organization (González 2015). We further this innovation by embedding shape-changing mechanisms throughout the fashion prototyping process, from the initial conceptualization to the final stages of draping and fitting. This approach aims to blend digital crafts with technical and conceptual innovation. Compared with the conventional fashion design approach that relies on static patterns and fixed forms, our dynamic approach enables designers to experiment with adaptable material. These materials are designed to be responsive to a variety of influences, such as embodied experience, environmental conditions, or specific functionalities (Sgro 2020). In this context, computation is approached as moldable physical materials that can be manipulated to enhance material properties and create new forms (Gowrishankar, Bredies and Ylirisku, 2017). Parameters of kinetic computational materials, such as velocity, path, and direction (Rasmussen et al. 2012) play a crucial role in defining the aesthetic qualities of a fashion piece. This necessitates a thorough examination of fashion design elements such as space, shape, and texture, as well as fashion design principles like rhythm, contrast, and proportion (Lee and Jirousek 2015), ensuring their harmonious integration with computational materials. By exploring the influence of these materials on fashion design variables, we aim to transcend limitations and elevate the fashion practice to a new level.

Computation, a key aspect of information technology, shares parallels with fashion and textile production processes like threading and weaving. These textile practices, underpinned by information technology principles, effectively weave information into their fabric through the use of mathematical models and metaphors such as strings, knots, and fabrics (Scafidi 2008). The logic of textile construction inherently mirrors computational processing, manifesting through codes, patterns, repeats, and variations (Schneiderman and Winton 2016). Building on the idea of fashion itself as technology leads to a convergence of fashion and computation into a seamless synergy, where fashion construction techniques, such as patterns and textures become integral to the overall wearable technology system. This concept is exemplified in projects like Aeolia, where Kettley and Briggs-Goode (2010) creatively integrated stretch sensor fibers into textiles such as weave, knit, and embroidery. They adopted a processual and open-ended method, focusing on textile attributes like texture, color, and touch over mere functionality. This mirrors computational thinking, with its emphasis on iterative exploration, systematic analysis, and adaptability for evolving solutions. Furthermore, Kettley et al (2010) highlighted the significance of the spaces between pattern pieces, experimenting with fabric density, blending rigid and flexible areas, and introducing conductive threads into seams. This innovative approach marries fashion, interaction design, and textile processes, striving to enhance both the aesthetic and functional facets of wearable technology. Our study will delve deeper into the natural alignment of fashion construction methods with computational approaches. This includes coding temporal fabric parameters, recording dynamic fabric patterns, and controlling shape-changing structures. Such an approach aims to not only improve the precision and efficiency of fashion practices but also to open new possibilities for creativity in materials and aesthetics.

Methods

The case study section of this paper provides an in-depth analysis of three studio-based design projects led by the first author, a Design Ph.D. student (referred to as 'the designer'), who possesses a combination of fashion design background and a passion for incorporating wearable technology into shape-changing fashion. Through collaboration with electrical engineers, she gained valuable insights into effectively incorporating technological tools (e.g., microcontrollers and actuators) and technological thinking (e.g., programming) into fashion design. The case study emphasizes practical skills, detailing the project requirements, formulated design frameworks, and future applications.

The design framework presented serves as a practical tool for designers to enhance their skills in cutting-edge design practices. It involves five iterative phases (Figure 1), including conceptualization and motivation, low-fidelity fabric samples, digitalizing shape-changing fabric samples, finalized/speculative prototypes, and envisioned future applications. Each phase involves a non-linear process of testing, evaluating, and refining ideas, fabric samples, or prototypes (van Zilt et al. 2022). This contrasts with the traditional linear fashion design framework, which typically follows a three-phase sequence: problem definition and research, creative exploration, and implementation (LaBat and Sokolowski 1999). Our design framework adopts an iterative development approach, progressively conceptualizing shape change through diverse stages, from initial understanding to practical samples, hands-on experimentation, and automated realizations, thereby refining the design. Moreover, unlike traditional industrial design projects, this study adopts a speculative rather than an outcome-oriented approach. It focuses on exploring uncharted creative possibilities and potential scenarios (Auger 2013). The following sections will delve deeper into each of these design phases.

- **Conceptualization and motivation:** The first phase involves researching and brainstorming design ideas, leading to the design brief. The designer draws inspiration from real-life shape-changing movements, such as those in dance performances and animal behaviors. Methods like sketches, collages, and desk research are used to generate ideas and analyze the movement morphology. To better understand body-material relationships, the designer performed material props on the body and used video recording techniques to capture the dynamics of movement (Castán and Tomico 2018). This exploration results in valuable data that informs a design brief that outlines the project's objectives, scope, and design theme, serving as a project guide.
- **Low-fidelity fabric samples:** The second phase involves creating low-fidelity fabric samples and iterative testing to generate knowledge and refine design

concepts in a tangible form. Material properties such as durability, texture, and color are explored to achieve the desired shape-changing effect, visual expression, and overall performance. To fully unlock fashion's potential in shape-change material design, textile manipulation techniques such as sewing and smocking are utilized. These methods trigger shape-changing behaviors, creating new design possibilities for form and craft (Gowrishankar, Bredies, and Ylirisku 2017). The kinetic parameters of the prototypes are examined to understand the underlying technical mechanisms driving the shape change.

- **Digitalizing shape-changing fabric samples:** This phase involves close collaboration with technicians to embed the circuits, actuators, and other e-components into the fabric. This integration realizes automatic material movement with digital mechanisms and physical programming.
- **Finalized/speculative prototypes:** In the fourth phase, the development of shape-changing garment involves finalizing or creating speculative prototypes to demonstrate the potential of the design concept. This phase requires the seamless integration of electronic components, which includes strategically placing these components for wearability and designing the circuit layout. Also, the incorporation of shape-changing elements requires innovative pattern-cutting and draping techniques to ensure fluidity and desired form. Attention is also given to managing trims and finishes associated with shape-changing elements (e.g., assembling inflatables). Finalized prototypes (e.g. case studies 1 and 3) prioritize functionality, scenarios, ease of use, and hedonic expectations (Koo, Dunne, and Bye 2014). Speculative prototypes (e.g., case study 2) explore imaginative variations in scale and form, inspiring future possibilities in shape-changing fashion.

- **Envisioned future application:** The showcased projects in this study vary in completion levels, ranging from fully realized functions to speculative designs awaiting further exploration. Driven by experimental practice rather than market demands, they foster discourse and narrative, enriching the perspectives and experiences of both users and designers (Flanagan 2017). In the final phase, the designer broadens their focus, considering the wider applications and implications of the design concept. This involves envisioning scenarios, assessing environmental impact, considering social relevance, and exploring aesthetic languages of the prototype in the context of future applications (Ferrara 2018).

Case Study 1: Textile-Flow--Creating Shape-Shifting Structures with Servo Motors

(1) Conceptualization and motivations

Textile-Flow aims to revolutionize conventional garments by incorporating dynamics, temporality, and energy into wearables, inspired by the fluid sleeve movements of the Chinese classical Water Sleeve Dance. In the Water Sleeve Dance, a dancer wears a gown with long sleeves that drape to the floor. As the dancer lifts and positions their arms, the sleeves respond to the forces of movements with dynamic curves, billows, and rotations (Erickson 1994). These transformed and entangled sleeves are regarded as an extension of bodily movement and emotional embodiment. In *Textile-Flow*, these textile structures are used to expand the design language of shape-changing mechanisms, fostering emotional and personalized fashion expression.

To unfold the morphology of fabric structures, the designer identified three main factors to consider: body mapping, design aesthetics, and material properties (Figure 2).

Through body mapping, the designer experimented with the strategic placement of water sleeves to inform intricate shape variations in sleeves. Drawing from body mapping insights, the designer engaged in creating sketches and collages, delving into the aesthetic elements of design, such as color, texture, and fabric shape. The goal was to craft an abstract, poetic, and ethereal visual effect, simultaneously conveying a slow and dreamy mood. To define the material properties, the designer explored various fabrics such as organza, linen, millinery, and chiffon to determine the characteristics including handle, stretchiness, durability, and weight, as described in Table 1. These properties were crucial in shaping the morphology, impacting the garment's functionality and aesthetics.

(2) Low-fidelity prototypes with winding structures

To achieve the desired shape changes in prototypes, the designer utilized unconventional techniques to construct winding structures for an unusual sleeve on the mannequin using organza and twisted boning (Figure 3). To manipulate shape changes, the designer attached a transparent thread underneath the boning. By pulling the thread by hand, the boning could be bent, resulting in a transformation in structures. The elasticity of the boning enabled the shape to instantly recover once the thread was released. Throughout the prototyping process, the designer identified various variables related to shape-changing mechanisms and forms:

- **Winding structure:** The winding structure of the garment was identified as a crucial element in creating unique three-dimensional forms that can expand and contract. Therefore, iterative refinement of the pattern is necessary.

- **Magnitude and direction of pulling force:** During the digital simulation, the magnitude and direction of the pulling force play a significant role in shaping the garment and affecting body movements.
- **Time of deformation and recovery:** The time required for the garment to deform and recover its shape should be considered to achieve a natural and gradual transformation. By attending to the often-neglected temporal structures of garments, we can expand both material expression and the body-material relationship (Bågander 2021).
- **Point of application of force:** The location of the actuators (devices that convert energy into motion or force to produce shape change) should be considered to avoid hindering body movement while achieving effective shape change.

(3) Digitalizing shape-changing fabric samples

In order to create a delicate sleeve structure that is layered, foldable, and rotatable, linen fabric and organza were spliced together. A servo motor was utilized as the primary pulling force, with its arm replaced by a bobbin that could wind both forward and in reverse. This allowed for the pulling and releasing of nylon thread, thus achieving the desired deformation and recovery effect. To ensure a slow, graceful, and natural transformation, the motor speed was adjusted accordingly. An Arduino Flora microcontroller (Adafruit 2023) was sewn into an internal pocket of the sleeve to control the motor, along with a battery and actuator placed in the same pocket (Figure 4). Additionally, a button was connected to the circuit and fixed around the cuff for the wearer's control.

(4) Finalized prototype

In the final prototype (Figure 5), winding elements and curved forms were applied throughout the entire design, creating a cohesive and harmonious aesthetic that echoes the unique sleeve structure. The internal pocket, specifically crafted to house essential electronic components, was designed to be detachable. This thoughtful feature grants the wearer flexibility to transition between static and dynamic looks effortlessly. To enhance wearability, we minimized the device’s weight by selecting a lightweight (10.5 grams) Lithium-Ion Polymer Battery (Adafruit 2023). This is essential as batteries are often the primary source of weight in wearable devices (Zeagler 2017). Additionally, to avoid interference with body movements during actuation, we placed the e-components in the internal pocket within the sleeve, at a distance from the body and joints.

(5) Envisioned future application

Incorporating intricate and eye-catching shape-changing structures into avant-garde garments challenges traditional ideas of how clothing should interact with the body. The resulting garments are tailored to fit the body and respond to the wearer's movements and behaviors, creating a spectacle of motion and fluidity. This transformative approach can reshape runway shows and red-carpet events, turning fashion into an interactive and discursive experience that engages both the audience and the wearer. Also, this kind of fashion emphasizes dynamic lines and energetic expressions achieved through shape-changing patterns and cuts. These elements contribute to a futuristic aesthetic that can find application in streetwear, providing constant novelty and enjoyment for the body (Balla 1973).

Discussion and Design Recommendations Drawn from Case Study 1

In summary, the Textile-Flow project inspires fashion practice by pushing the boundaries of traditional garment design and construction, fosters creativity through sensory engagement and expressive design, and enhances technical thinking by integrating digital tools and exploring the mechanics of garment movement.

This project exemplifies the critical role of a dynamic and iterative design approach in fashion practice, emphasizing the value of continual prototyping and refinement for achieving creative solutions. It traces the progression from low-fidelity mocking up to technology-embedded digitalization, showcasing a consistent problem-solving mindset. The designer's continuous prototyping on mannequins facilitated constant variations in the size, structure, and form of the garment, mirroring the fluid and experimental nature of parametric design. Although the fashion industry has adopted computer-aided parametrical design tools like Grasshopper to manipulate fabric shape and layering to generate free-form surfaces (Jeong et al. 2021), the project highlights the underutilized potential of hands-on parametric methods in fashion prototyping. While digital tools offer precision, working with physical fabrics provides an intuitive understanding of form and texture that is difficult to replicate digitally. Future research should delve into how this hands-on approach, infused with parametric design principles, unlocks new creative possibilities in fabric manipulation and garment construction. This exploration could potentially lead to new methodologies and designs that blend traditional crafts with modern technology, enhancing both creativity and technical proficiency in fashion practice.

This project advocates for a sensory-driven approach to creativity, encouraging the use of tactile and visual sensations as primary sources of creative inspiration in fashion practice. Reflecting the insights of Petreca, Baurley, and Bianchi-Berthouze (2015), it highlights the opportunity for fashion designers to leverage their own tactile and visual sensations to make situated design responses. This approach enables designers to respond aptly to the specificities of their design context, accurately simulate material behaviors, and effectively evoke emotional and imaginative responses. We recommend future research embrace a hands-on craft approach throughout each stage of the creative process to address the emerging parameters in fashion practice.

This project elevates technological thinking by exploring of kinetic parameters of the actuated garment, including magnitude and direction of pulling force, time of deformation and recovery, point of application of force, and shape-changing speed. This enhanced understanding of temporal dynamics informs the approach to pattern-cutting, allowing for designs that adapt and morph over time in response to these forces. Additionally, the project goes beyond mere physical alterations, considering how the perceived qualities of these kinetic parameters, such as their speed, can create more natural material movements in materials. Recognizing the importance of both expressive and sensory dimensions in these kinetic parameters marks a significant advancement in design thinking, resonating with the findings of Rasmussen et al. (2012) who highlighted the necessity of integrating both physical and expressive parameters to influence user experience and effectively convey the designer's intentions. Therefore, our recommendation for future works is to conduct comprehensive investigations into the relationship between kinetic parameters, interaction expressivity, and sensory experience as a holistic approach to fashion practice.

Case Study 2: The Elephant Dress-- Incorporating Coding System into fabric manipulation

(1) Conceptualization and motivations

The Elephant Dress is a speculative project exploring flexible shape changes in fabric and garment structures to realize sustainable design (Figure 6). Drawing inspiration from the muscle movements of the elephant trunk, the project aims to create versatile structures and styles in one garment, catering to the wearer's preferences and needs. During prototyping, the primary objective is to emulate the crisscrossing muscle fibers of the elephant trunk, thereby enabling a wide array of shape changes within a single fabric sample. To further enhance its sustainable approach, the project incorporates the principles of zero-waste cutting. This seamless integration aligns with the main goal of creating adaptable garments that minimize their environmental impact. The inherent flexibility embedded within the fabric's ability to morph in shape plays a pivotal role in advancing the zero-waste cutting approach. This adaptability facilitates the effortless transformation of the fabric into various dimensions, ensuring a precise fit on the wearer's body. Significantly, this is achieved without resorting to traditional darting techniques or excessive cuts.

(2) Low-fidelity prototypes with shirring

During this phase, the designer utilized the shirring technique to create shape-changing forms, stretching and manipulating fabric in specific directions (Figure 7). Three layers of shirred fabrics were stitched together at their four edges to form a cohesive composite fabric, echoing the layered, crisscross muscle fibers of an elephant trunk. This fabric can be deformed through thread manipulation, with each layer contracting in different directions: horizontally for the first layer, vertically for the second layer, and diagonally for the third layer. Thread manipulation was systematically coded: letters representing the thread and numerical values indicating the length pulled out. This coding (e.g., A3D5H7) precisely documented each fabric deformation. Although non-technological, this approach refined traditional smocking, opening new design avenues through innovative thought. Using the coding method, the designer created variations in fabric structures. For instance, in a three-layer fabric with three rows of shirring stitches on each layer, there will be nine different threads. These threads in various combinations and lengths, facilitated diverse grouping methods. This pyramid-like thread selection and manipulation yielded a complex array of shape-changing effects across the fabric. The forces applied to the selected threads distribute across the entire composite fabric, causing adjacent areas to experience varying levels of deformation as well. Consequently, the fabric exhibited a dynamic range of changes, with some areas experiencing subtle shifts while others underwent pronounced alterations. Additionally, there could be unexpected and surprising emergent patterns, adding a layer of complexity to the final result.

(3) Digitalizing shape-changing fabric samples

Informed by the variables of shirring techniques (e.g., direction, length), the designer tried to translate the shirring languages and simulate the shrinking behaviors by applying shape memory alloys (SMA) (Figure 8). A spring-like Nickel-Titanium memory alloy wire with a 70% contraction rate was used, capable of contracting upon the application of electric current. To mimic the hand-shirring technique, the designer marked the shirred pattern on the back of the fabric, precisely defining the shrinking location, direction, and length. The SMA wire was then cut into uniform segments on strategically placed on the fabric, aligning with the designated shirred pattern. These wires were subsequently welded at both ends to form a complete circuit. Activating the current causes the SMA segments to contract between certain points, reducing the distance between points and mimicking the traditional shirring process. The degree of shrinkage was determined by varying the duration of the current, akin to adjusting the length of the thread pulled in the low-fidelity prototypes, thereby offering precise control over the fabric’s transformation.

In this application, SMA segments connected in the same circuit can contract together, like how a row of threads behaves in each layer of the low-fidelity prototype. Each circuit acts as a separate entity, providing precise control to achieve optimal shape-changing effects. Also, we tried to link different rows of the SMA segments together within one circuit, forming a complex shirring pattern with shrinkage in horizontal, vertical, and diagonal directions in one layer. Compared with low-fi prototypes, SMA-incorporated shape-changing fabrics enable automatic shape alteration, eliminating the need for manual thread pulling.

(4) Speculative prototypes

While SMAs hold promise for future exploration, the immediate goal was to leverage the shirring patterns for rapid prototyping. Integrating SMA into larger-scale prototyping poses several challenges, notably the high temperatures generated by the circuits, rendering it unsuitable for wearable applications. Additionally, the relatively high cost of SMA makes it less ideal for cost-effective rapid prototyping. Therefore, to facilitate practical and efficient prototyping while preserving the fabric's draping ability, our focus centered on the low-fi shirring technique. This strategic decision aligns perfectly with our design philosophy, as we interrogate the underlying technological thinking and regard textile logic as the foundation for programmable material systems (Scott 2018). By adopting this approach, we achieved better manageability throughout the design process. The resulting speculative prototypes push the boundaries of fashion, leveraging embedded shape-changing patterns to enhance temporal structures. During the speculative prototyping phase, the designer combined coded shirring with zero-waste cutting techniques to revolutionize the traditional form-giving process. By integrating the coding system into a one-meter squared fabric composite, the designer draped the fabric on the mannequin. By manipulating specific areas, they crafted three-dimensional functional structures such as waistlines and collars directly on the form. This innovative approach eliminates traditional tailoring, thus reducing fabric waste caused by cutting and trimming (Figure 9).

(5) Realization

This project offers an effective approach to sustainable fashion and customized garments. One garment can adapt to versatile scenarios by altering dimensions such as scale, texture, and silhouette, creating various styles for occasions and daily wear. With elastic properties, these garments can be customized to fit individual body types, providing a one-garment-fits-all solution.

The integration of the coding system can enhance the production-consumption relationship. This allows customers to efficiently order specific pieces, adding a sense of individuality and exclusivity to the garments, as exemplified by Maison Margiela's unique numerical identifiers (Marigorta 2021). This strategy can potentially strengthen the connection between customers and fashion brands.

Discussion and Design Recommendations Drawn from Case Study 2

This project demonstrates creativity through the fusion of biomimetic inspiration from elephant trunk movements, inventive experiments with SMA, and creative shirring techniques, expanding traditional textile design boundaries. This aligns with Sgro's (2014) proposition that mimicking animal movement catalyzes dynamic designs and innovative textiles, achieving a harmonious synthesis of aesthetics and functionality in fashion, mirroring the elegance and adaptability found in nature. Thus, we recommend that future research continues to explore and innovate in biomimicry through textile manipulation.

This project exemplifies technological thinking in fashion by innovatively integrating coding with textile manipulation, digitalizing traditional shirring techniques through shape memory alloys, and evolving prototypes to demonstrate a fusion of technology and craft. This project utilized numerical coding as a communicative tool for storing, retrieving, and interpreting dynamic changes in fabric structures, enhancing the accuracy and efficiency of the research process. We recommend adopting coded fabric manipulation in future research, as it facilitates the exchange of information and knowledge between different parties to drive systematic and innovative design solutions.

During design practice, this project demonstrates the fusion of fashion craft and technological thinking, creating new design vocabularies and possibilities, resonating withwith Harris's (2012) concept of combining digital and traditional crafts for enhanced creativity. The SMA experiment, translating textile techniques into computational design patterns, provided deeper insights into the material behavior and possibilities for shape-changing designs. Furthermore, the synergy of zero-waste cutting and coded shirring highlights the potential of technological thinking as design material, reshaping how fabrics are layered, folded, manipulated, and seamlessly integrated (Dongen et al. 2019). We suggest further exploration of coded shirring within the zero-waste cutting framework to advance design iterations. This integration not only augments adaptability and efficiency but also promotes real-time fabric transformations and ecological alignment. It establishes a feedback loop that harmonizes malleability and precision, balancing aesthetics and sustainability. This innovative amalgamation not only fosters creativity and environmental stewardship but also signals a significant shift in design paradigms, advocating for a sustainable and creative future in fashion design.

Case Study 3: The Pneum-Muscle--draping with pneumatics

(1) Conceptualization and motivations

The *Pneum-Muscle* project draws inspiration from the functioning of human muscles, which generate movement by pulling on tendons and bones through contraction (Figure 10). During desk research, the designer discovered the use of pneumatic mechanisms in rehabilitation wear. These pliable, tube-like silicone muscles expand with the introduction of air. By regulating the amount, timing, and pattern of airflow, the pneumatic system can simulate the contraction of a human muscle, providing supplementary support during body movement.

The integration of pneumatic technology into fashion draping can fulfill a variety of motivations (Figure 11). First, on a somatic level, pneumatic structures can aid body movement, expand the range of motion, and enhance overall comfort. At the aesthetic level, the integration of pneumatic technology in fashion design offers a unique expression of fluid identity, emphasizing interactive and flexible movement that challenges traditional concepts of garment form. Furthermore, by designing pneumatic apparel with user-controlled systems, wearers can effortlessly modify the shape and fit of the garment to align with their preferences or requirements. This personalized and flexible customization empowers wearers to participate in the design process, fostering a more engaging and immersive user experience.

(2) Low-fidelity prototypes with balloons

During the low-fidelity prototyping process, the designer utilized a variety of materials, such as long balloons, pumps, calico, and spandex fabrics, to construct three-dimensional shapes. The whole prototyping process can be divided into the following three steps: Embedding inflatables, draping, and fitting (Figure 12).

- **Embedding inflatables:** To incorporate the inflatables into the garment structure, the designer inserted the balloons into a fabric tunnel of the appropriate size. This involves measuring the diameter of the fully inflated balloon and creating a fabric sleeve that can accommodate it. The choice of material for the fabric sleeve is critical; a stretchy fabric allows for a slightly smaller tunnel width than the balloon diameter, whereas a non-stretch fabric requires more space. The actual measurement of the tunnel width may vary depending on the fabric used, and testing is necessary before draping to ensure accuracy.
- **Draping:** During the draping phase, the designer intertwined, connected, and overlapped the balloons to create imaginative structures that spanned across various body parts and muscle groups, forming intricate three-dimensional lines. The inflation process was manually controlled using a pump, and different volume levels were observed to bring about diverse transformations in the structures. The use of calico and spandex fabric tunnels resulted in varying styles, with calico presenting a clean and crisp appearance, and spandex offering a more natural aesthetic.
- **Fitting:** After completing the initial prototypes, the designer tested and modified them by wearing them on her own body. This allowed her to determine the optimal design solution that would enhance the overall wearing experience and improve comfort during body movements.

(3) Digitalized shape-changing wearable design

To achieve the desired shape-changing behavior of the garment, the designer replaced the original long balloons with custom-made inflatables constructed from TPU fabric with sealed seams. Unlike latex balloons, the TPU-manufactured tubes provide greater shape control due to their reduced elasticity. This property allowed the designer to translate the shapes generated with the latex balloons into precise patterns suitable for industrial manufacturing. The use of TPU fabric not only enhanced the accuracy and repeatability of the shape-changing effects but also smoothed the transition from low-fidelity prototypes to production-ready final garments. These inflatables were connected to small digital pumps through inflation tubes. The pumps were then linked to actuation boards and a circuit that controlled the inflation time, resulting in a range of structures for the prototype (Figure 13). However, two main challenges were encountered. Firstly, the rather thin fabric cannot hold the TPU inflatables tightly, resulting in difficulties in achieving smooth shape changes. To address this issue and avoid unintended shape alterations, selecting a fabric with appropriate stiffness for the inflatable sleeves was essential, as it helps to restrict random pneumatic movements. In addition, it was necessary to connect multiple air pumps to the inflatables through tubes and place them in stable and concealed locations to maintain the garment's aesthetic appeal. These challenges need to be addressed in the finalized prototype.

(4) Finalized prototype

The designer overcame the challenges by selecting a stiff spandex fabric that avoided excessive elasticity or thinness to maintain the intended shapes and positions of inflatables. This resulted in a sculptural and flowing silhouette compared to the previous soft appearance. On-body tests were conducted to optimize the inflatable's shape, location, strength, and resulting sensations. To ensure stability and concealment, digital pumps were integrated onto an internal detachable vest's belt. The remote-control system was established with four buttons designated to control the inflation time on the garment's four symmetrical parts: chest, shoulder, back, and sleeve. This enabled the wearer to achieve various shapes and added interactivity and playfulness to the garment's functionality (Figure 14).

(5) Envisioned application

The proposed pneumatic draping method can revolutionize the way we experience wearables. By offering tailored support to specific areas of the body, it holds the promise of significantly improving effectiveness and comfort. This approach improves user satisfaction by tailoring pneumatic wearables to individual needs. To fully realize the potential of this method, the collaboration between fashion and interaction designers is needed. It ensures a thorough evaluation of user experience aligns the design with user requirements. Furthermore, the playful manipulation and innovative interactive forms of pneumatic wearables can be integrated into entertainment, such as games, to enhance user perceptions and engagement. Pneumatic draping can also inspire creativity in performance art, enabling artists to create unique visual experiences that captivate the audience.

Discussion and Design Recommendations Drawn from Case Study 3

This project significantly advances fashion practice and creativity leveraging pneumatic technology to redefine garment aesthetics and functionality. This innovative approach moves beyond traditional fabric shaping, introducing complex shapes, unique expressiveness, and versatile experiences. This finding aligns with the early pneumatic design project Awakened Apparel (Perovich, Mothersill, and Farah 2013), highlighting how pneumatic technology enhances the informational, emotional, and functional dimensions of fashion. By moving away from the often inaccessible technical requirements of laboratory-based pneumatic processing, this study introduces a more feasible, speedy, and efficient method for fashion designers to experiment with draping on their familiar mannequins. This method can minimize costs and enable designers to generate ideas quickly, bridging the gap between high-tech engineering and everyday fashion practice.

The fusion of tunnel structures with pneumatic actuation exemplifies how technological thinking can elevate and transform the craft of fashion design. In future research, we recommend that designers further explore the fusion of pneumatics with fashion construction techniques. This could involve combining pneumatic actuation with elasticity-enhancing techniques such as knitting, weaving, and laser cutting to create new tensions, textures, and volume changes in fabrics. Also, pneumatics offer advanced control over garment shaping, allowing for precision in design previously unattainable. By strategically inflating and deflating specific areas of a garment, designers can create intricate shapes and structures not achievable through traditional means. This opens new design possibilities and enables designers to push the boundaries. To further explore the control of material behaviors in pneumatic fashion, we recommend that designers experiment with various fabrics and materials, paying particular attention to how their elastic properties interact with pneumatic influences. Additionally, testing different inflation and deflation patterns can help designers comprehend how they influence the shape and structure of the garment. Furthermore, by integrating sensors and microcontrollers, designers can create responsive garments that dynamically adapt to the wearer's needs and preferences. Such advancements not only highlight the symbiotic relationship between fashion and technology but also pave the way for more personalized, interactive, and functional fashion experiences in the future.

Limitations, conclusions, and future works

This study does have certain limitations. The approach taken in examining the design cases is rooted in a first-person perspective, serving as a means to acquire and share knowledge. However, it is essential to acknowledge that different practitioners may hold diverse perceptions regarding prototypes, skill requirements, and design choices. To address this, our future intention is to engage practitioners as subjects to comprehensively evaluate the effectiveness of the methods generated. Furthermore, the design methods presented herein can be developed into toolkits aimed at facilitating the creative prototyping process. These toolkits can then be refined based on user testing and feedback, ensuring their practicality and usefulness. Despite these limitations, the three design cases have yielded insights that extend beyond the realm of shape-changing mechanisms. They offer design qualities and philosophies that possess broader applicability and relevance. These findings encompass innovative design principles, novel ways of communicating design ideas, and a deeper understanding of the relationship between the human body and materials. These insights lay fertile ground for future exploration, as elaborated upon in the subsequent discussion.

For future investigations, a crucial focus is to address design variables relationally. By incorporating technological components with shape-changing parameters (e.g., location, form, and pattern), designers can unlock more dynamic and expressive solutions associated with fashion prototyping. This approach compels designers to finely balance design variables, allowing for innovative tensions. Case 1 serves as a prime example where the role of the servo motor in shaping sleeve patterns showcases the interconnectedness of design variables. The motor's speed, torque, fabric weight, texture, and properties intertwine in a fascinating interplay, generating versatile design possibilities. These factors delicately balance to influence the garment's overall appearance, lending it a perceived naturalness and softness that elevate its appeal and enhance the wearer's experience. Similarly, Case 3 reinforces this relational approach, highlighting the importance of harmonizing fabric sleeve weight and stretch with inflatable elasticity. The pairing of these elements leads to distinct variations in the forms and aesthetics of the garment, demonstrating how subtle tweaks in design variables can yield different outcomes. Future research can continue to explore and refine this relational approach, leveraging technology to dynamically adjust design variables in response to one another. This innovation has the potential to create garments that transcend static limitations, adapting seamlessly to evolving user needs. Moreover, delving into novel materials and cutting-edge fabrication techniques can amplify the potential of this approach, facilitating the creation of garments that seamlessly blend the domains of fashion, art, and technology.

Also, fostering a shared vocabulary between fashion practice and technical design is crucial. Embracing computational thinking in fashion design not only refines problem-solving but also boosts communication with technologists and systematic documentation of ideas and prototypes. Case 2 exemplifies this by introducing coding for fabric manipulation, yielding a spectrum of shape-changing patterns. Such variations in parameters of fabric shrinking were translated into the layout of the SMA segments, leading to optimized shape-changing material behavior. On the other hand, technological tools offer designers an advanced level of control over the shape and structure of garments, facilitating the creation of responsive and situated garments in a dynamic way. For instance, in case 3, the inflation process enables the designer to observe, evaluate and optimize the shape, space, and silhouette at different levels. The translation of unconventional technical dimensions of time, space, and movement into shape-changing fashion prototyping languages introduces interactivity, fluidity, and energy to apparel, inspiring creativity in manufacturing (e.g. pattern-cutting, finishes) and ways of utilization (e.g.controling of variations in styles).

Furthermore, shape-changing prototyping reshapes the body-material relationship. Case 1 exemplifies how human performance contributes to the temporality of garment structures to challenge conventional static boundaries. This aligns with Gemeinboeck's (2021) enactive and embodied approach, where human performance intertwines with materials, contributing to movement qualities and material affordances. Future research can delve deeper into this body-material entanglement for leveraging the body's kinaesthetic dimension to shape garments. Vice versa, the shape-changing garment expands the body's performance and sensations. Its vibrant qualities permeate the intrabody processing, heightening the wearer's consciousness of ongoing material transformation and fostering a deeper mutual alliance between the body and the wearable (Tsaknaki et al., 2021). Case 3, for instance, blurs garment-skin boundaries, enhances body movement range, and introduces caring experiences through inflatable-induced pressures, disrupting conventional garment structures. This versatile expression prompts novel body-material scenarios. This aligns with Kao et al. 's (2017) kinetic wearable, illustrating how material mobility and its proximity to the body convey personalized aesthetics, interaction, and meaning. It is meaningful for future research to reconsider how to utilize shape-change embedded garments to revolutionize dynamic relationships, attachments, and alignments between body and material.

In conclusion, the case studies presented in this study demonstrate the potential for shape-changing mechanisms and technological thinking to revolutionize traditional garment design techniques and manufacturing processes. Such a paradigm shift can stimulate interdisciplinary dialogues for new design methods, spur the development of new formation and temporal patterns of garments, and open up more space in relation to the body and environment (Dumitrescu 2013). However, these advancements also give rise to broader issues that need to be addressed, such as sustainability, the evolving needs of consumers, and ethical concerns in fashion. As such, it is crucial for designers to incorporate these considerations into their work and continue to push the boundaries of what is possible in fashion practice through the incorporation of shape-changing mechanisms and technological thinking.

Disclosure Statement:
No potential conflict of interest was reported by the authors.

References

Andersen, Kristina, Bruna Goveia da Rocha, Oscar Tomico, Marina Toeters, Angella Mackey, and Troy Nachtigall. 2019. ‘Digital Craftsmanship in the Wearable Senses Lab’. In *Proceedings of the 23rd International Symposium on Wearable Computers*, 257–60. London United Kingdom: ACM. doi:10.1145/3341163.3346943.

Auger, James. 2013. ‘Speculative Design: Crafting the Speculation’. *Digital Creativity* 24 (1): 11–35. doi:10.1080/14626268.2013.767276.

Bågander, Linnea. 2021. ‘Body Movement as Material: Designing Temporal Expressions’. Högskolan i Borås.

Balla, Giacomo. 1973. ‘Futurist Manifesto of Men’s Clothing 1913.”’. *Trans. Robert Brain. Futurist Manifestos. Ed. Umbro Apollonio. New York: Viking Press*, 132–34.

Bequette, James W., and Marjorie Bullitt Bequette. 2012. ‘A Place for Art and Design Education in the STEM Conversation’. *Art Education* 65 (2): 40–47. doi:10.1080/00043125.2012.11519167.

Castán, Marina, and Oscar Tomico. 2018. ‘“Layering up” Soft Materiality: A Hybrid Embodied Design Ideation Method for Soft Interior Architectural Design’. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction*, 60–72. Oslo Norway: ACM. doi:10.1145/3240167.3240210.

Dassen, Wendy, and Miguel Bruns Alonso. 2017. ‘Aesthetics of Haptics: An Experience Approach to Haptic Interaction Design’. In *Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems*, 254–59. Edinburgh United Kingdom: ACM. doi:10.1145/3064857.3079156.

Dongen, Pauline Van, Ron Wakkary, Oscar Tomico, and Stephen Wensveen. 2019. ‘Towards a Postphenomenological Approach to Wearable Technology through Design Journeys’. Loughborough University, 526167 Bytes. doi:10.17028/RD.LBORO.9724649.

Dumitrescu, Delia. 2013. ‘Relational Textiles: Surface Expressions in Space Design’. University of Borås.

Erickson, Susan N. 1994. ‘«Twirling Their Long Sleeves, They Dance Again and Again...»: Jade Plaque Sleeve Dancers of the Western Han Dynasty’. *Ars Orientalis* 24: 39–63.

Ferrara, Marinella. 2018. ‘Smart Experience in Fashion Design: A Speculative Analysis of Smart Material Systems Applications’. *Arts* 8 (1): 4. doi:10.3390/arts8010004.

Flanagan, Patricia. 2017. ‘Critical and Speculative Wearables: Boundary Objects’. In *Design, User Experience, and Usability: Designing Pleasurable Experiences*, edited by Aaron Marcus and Wentao Wang, 656–72. Lecture Notes in Computer Science. Cham: Springer International Publishing. doi:10.1007/978-3-319-58637-3_51.

Freire, Rachel, Paul Strohmeier, Cedric Honnet, Jarrod Knibbe, and Sophia Brueckner. 2018. ‘Designing eTextiles for the Body: Shape, Volume & Motion’. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*, 728–31. Stockholm Sweden: ACM. doi:10.1145/3173225.3173331.

Gemeinboeck, Petra. 2021. ‘The Aesthetics of Encounter: A Relational-Performative Design Approach to Human-Robot Interaction’. *Frontiers in Robotics and AI* 7. https://www.frontiersin.org/articles/10.3389/frobt.2020.577900.

Genç, Çağlar, Oğuz Turan Buruk, Sejda İnal Yılmaz, Kemal Can, and Oğuzhan Özcan. 2018. ‘Exploring Computational Materials for Fashion’: 12 (3): 19.

González, Marcos Román. 2015. ‘COMPUTATIONAL THINKING TEST: DESIGN GUIDELINES AND CONTENT VALIDATION’. Unpublished. doi:10.13140/RG.2.1.4203.4329.

Gowrishankar, Ramyah, Katharina Bredies, and Salu Ylirisku. 2017. ‘A Strategy for Material-Specific e-Textile Interaction Design’. In *Smart Textiles*, edited by Stefan Schneegass and Oliver Amft, 233–57. Human–Computer Interaction

Series. Cham: Springer International Publishing. doi:10.1007/978-3-319-50124-6_11.

Harris, Jane. 2012. ‘Digital Practice in Material Hands: How Craft and Computing Practices Are Advancing Digital Aesthetic and Conceptual Methods’. *Craft Research* 3 (1): 91–112. doi:10.1386/crre.3.1.91_1.

Huang, Xinyi, Sarah Kettley, Sophia Lycouris, and Yu Yao. 2023. ‘Autobiographical Design for Emotional Durability through Digital Transformable Fashion and Textiles’. *Sustainability* 15 (5). Multidisciplinary Digital Publishing Institute: 4451. doi:10.3390/su15054451.

Industries, Adafruit. 2023a. ‘FLORA - Wearable Electronic Platform: Arduino-Compatible’. Accessed April 7. https://www.adafruit.com/product/659.

———. 2023b. ‘Lithium Ion Polymer Battery - 3.7v 500mAh’. Accessed April 7. https://www.adafruit.com/product/1578.

Jeong, Jiwoon, Hyein Park, Yoojeong Lee, Jihye Kang, and Jaehoon Chun. 2021. ‘Developing Parametric Design Fashion Products Using 3D Printing Technology’. *Fashion and Textiles* 8 (1): 22. doi:10.1186/s40691-021-00247-8.

Kao, Hsin-Liu (Cindy), Deborah Ajilo, Oksana Anilionyte, Artem Dementyev, Inrak Choi, Sean Follmer, and Chris Schmandt. 2017. ‘Exploring Interactions and Perceptions of Kinetic Wearables’. In *Proceedings of the 2017 Conference on Designing Interactive Systems*, 391–96. DIS ’17. New York, NY, USA: Association for Computing Machinery. doi:10.1145/3064663.3064686.

Kettley, Sarah, and Amanda Briggs-Goode. 2010. ‘Aeolia: Textile Enquiry and Design’. *Duck: Journal for Textiles Research and Textile Design* 1. University of Loughborough (DUCK).

Kettley, Sarah, Tina Downes, Karen Harrigan, and Martha Glazzard. 2010. ‘Fit for Purpose? Pattern Cutting and Seams in Wearables Development’. *Digital Creativity*, December. Routledge. https://www.tandfonline.com/doi/abs/10.1080/14626268.2010.548870.

Kim, Changhwan, Gibaek Kim, Youngbin Lee, Giuk Lee, Seungyong Han, Daeshik Kang, Sumin Helen Koo, and Je-sung Koh. 2020. ‘Shape Memory Alloy Actuator-Embedded Smart Clothes for Ankle Assistance’. *Smart Materials and Structures* 29 (5): 055003. doi:10.1088/1361-665X/ab78b5.

Kontovourkis, Odysseas, Marios C. Phocas, and George Tryfonos. 2013. ‘Prototyping of an Adaptive Structure Based on Physical Conditions’. *International Journal of Architectural Computing* 11 (2): 205–25. doi:10.1260/1478-0771.11.2.205.

Koo, Helen Sumin, Lucy Dunne, and Elizabeth Bye. 2014. ‘Design Functions in Transformable Garments for Sustainability’. *International Journal of Fashion Design, Technology and Education* 7 (1): 10–20. doi:10.1080/17543266.2013.845250.

LaBat, Karen L., and Susan L. Sokolowski. 1999. ‘A Three-Stage Design Process Applied to an Industry-University Textile Product Design Project’. *Clothing and Textiles Research Journal* 17 (1): 11–20. doi:10.1177/0887302X9901700102.

Lee, Jung Soo, and Charlotte Jirousek. 2015. ‘The Development of Design Ideas in the Early Apparel Design Process: A Pilot Study’. *International Journal of Fashion Design, Technology and Education* 8 (2): 151–61. doi:10.1080/17543266.2015.1026411.

Marigorta, Carmen. 2021. ‘Margiela’s Numbers... What Does Each One Mean?’ *HIGHXTAR*. February 15. https://highxtar.com/martin-margiela-numerical-curiosities-you-didnt-know/?lang=en.

Nabil, Sara, Jan Kučera, Nikoletta Karastathi, David S. Kirk, and Peter Wright. 2019. ‘Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation’. In *Proceedings of the 2019 on Designing Interactive Systems Conference*, 987–99. San Diego CA USA: ACM. doi:10.1145/3322276.3322369.

Perovich, Laura, Philippa Mothersill, and Jennifer Broutin Farah. 2013. ‘Awakened Apparel: Embedded Soft Actuators for Expressive Fashion and Functional Garments’. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction - TEI ’14*, 77–80. Munich, Germany: ACM Press. doi:10.1145/2540930.2540958.

Petreca, Bruna, Sharon Baurley, and Nadia Bianchi-Berthouze. 2015. ‘How Do Designers Feel Textiles?’ In *2015 International Conference on Affective Computing and Intelligent Interaction (ACII)*, 982–87. doi:10.1109/ACII.2015.7344695.

Rasmussen, Majken K., Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. ‘Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions’. In *Proceedings of the SIGCHI Conference on*

Human Factors in Computing Systems, 735–44. Austin Texas USA: ACM. doi:10.1145/2207676.2207781.

Scafidi, Susan. 2008. ‘FIT: Fashion as Information Technology’. *Syracuse L. Rev.* 59. HeinOnline: 69.

Schneiderman, Deborah, and Alexa Griffith Winton, eds. 2016. *Textile Technology and Design: From Interior Space to Outer Space*. London ; New York: Bloomsbury Academic, an imprint of Bloomsbury Publishing Plc.

Scott, Jane. 2018. ‘Responsive Knit: The Evolution of a Programmable Material System’. In *Proceedings of DRS2018*, 4:1800–1811. Design Research Society.

Sgro, Donna. 2014. ‘Metamorphoric Fashion: A Transformative Practice’, 22.

———. 2020. ‘Dynamic Cutting Using Material Engagement with Textiles in Pattern Cutting for Fashion Design Practice’. *Journal of Textile Design Research and Practice* 8 (2): 232–55. doi:10.1080/20511787.2020.1728101.

Toeters, M. J., and L. M. G. Feijs. 2014. ‘Actuating Movement in Refined Wearables’. In *Global Fashion Gent, Nov. 20-21, 2014*.

Townsend, Katherine, and Fiona Mills. 2013. ‘Mastering Zero: How the Pursuit of Less Waste Leads to More Creative Pattern Cutting’. *International Journal of Fashion Design, Technology and Education* 6 (2): 104–11. doi:10.1080/17543266.2013.793746.

Tsaknaki, Vasiliki. 2021. ‘The Breathing Wings: An Autobiographical Soma Design Exploration of Touch Qualities through Shape-Change Materials’. In *Designing Interactive Systems Conference 2021*, 1266–79. DIS ’21. New York, NY, USA: Association for Computing Machinery. doi:10.1145/3461778.3462054.

Tsaknaki, Vasiliki, Karey Helms, Marie Louise Juul Søndergaard, and Marianela Ciolfi Felice. 2021. ‘“Vibrant Wearables”: Material Encounters with the Body as a Soft System’. *Journal of Textile Design Research and Practice* 9 (2): 142–63. doi:10.1080/20511787.2021.1923202.

Vallgårda, Anna, Laurens Boer, Vasiliki Tsaknaki, and Dag Svanæs. 2017. ‘Material Programming’. *Interactions* 24 (3): 36–41. doi:10.1145/3057277.

Yair, Karen, Anne Tomes, and Mike Press. 1999. ‘Design through Making: Crafts Knowledge as Facilitator to Collaborative New Product Development’. *Design Studies* 20 (6): 495–515. doi:10.1016/S0142-694X(98)00040-4.

Zeagler, Clint. 2017. ‘Where to Wear It: Functional, Technical, and Social Considerations in on-Body Location for Wearable Technology 20 Years of

Designing for Wearability'. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers*, 150–57. ISWC '17. New York, NY, USA: Association for Computing Machinery. doi:10.1145/3123021.3123042.

Zilt, Julia van, Amy Winters, Hannah Carlotta Kelbel, and Miguel Bruns. 2022. 'The Design Process of a Multi-Disciplinary Tool for Developing Interactive Textiles'. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*, 1–16. Daejeon Republic of Korea: ACM. doi:10.1145/3490149.3502258.

Fabric	**Handle/Texture**	**Stretchiness**	**Durability**	**Weight**
Organza	Stiff, Crisp	No stretch	Delicate	Light
Linen	Textured, Rough	Some stretch	Durable	Medium
Millinery	Smooth	No stretch	Delicate	Light
Chiffon	Soft, Flowing	Some stretch	Delicate	Light

Table1. Material properties of fabrics.

Figure caption list:

Figure 1. The process of shape-change incorporated fashion prototyping.

Figure 2. The exploration of material morphology.

Figure 3. Design variables emerged from the low-fidelity prototype.

Figure 4. The digitalized shape-changing sleeve.

Figure 5. The finalized garment

Figure 6. The prototype of the Elephant Dress

Figure 7. Low-fidelity shirred fabric samples

Figure 8. Automatic shrinking fabric with SMA embedded.

Figure 9. Zero-waste cut prototypes.

Figure 10. Motivations of the project.

Figure 11. The Pneum-Muscle project

Figure 12. Low-fidelity prototypes with balloons

Figure 13. Digitalized prototype.

Figure 14. The finalized prototype.