HaptiFab: A Wearable Toolkit Supports the Integration of Haptic Actuator and Fabric for Interdisciplinary Design

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Fig. 1. HaptiFab's application in interdisciplinary design: a) an overview of the HaptiFab toolkit, b) participants using the kit to create, c) the integration of the haptic actuator with the fabric, d) the final presentation of the wearable prototype.

Integrating different haptic sensations into wearable technology poses complex challenges due to the variety of options and the interdisciplinary expertise required. A key limitation is the absence of effective tools to assist designers and engineers create prototypes. In this paper, we first conducted a formative study and identified our design goals. We then proposed HaptiFab, a wearable toolkit that integrates a haptic actuator with fabric, enabling interdisciplinary groups to create wearable prototypes effectively. Through a five-day workshop with 30 participants from interdisciplinary backgrounds, we conducted a mixed-method analysis, demonstrating HaptiFab's ability to support varied design goals with low learning barriers and high design efficiency for interdisciplinary groups. We provide a detailed report on participants' goals, interactions, considerations, and potential design spaces enabled by HaptiFab. Drawing on these findings, we discuss the advantages of combining haptic actuators to make different sensations with fabric, which could empower interdisciplinary groups to create innovative, practical, and emotionally resonant wearable technologies for diverse user scenarios.

CCS Concepts: • **Human-centered computing → Systems and tools for interaction design**.

Additional Key Words and Phrases: Haptic Actuator, Wearable Technology, Fabric, Haptic Sensation, Interdisciplinary Design

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1 INTRODUCTION

Haptics is an important form of sensation that assists wearable technologies in realizing specific functions, conveying affective information, and improving psychological experiences due to its wide distribution across the surface of human skin [1, 2]. Recent research has transferred physically-grounded haptic interfaces [3] to haptic actuators [4], which allows users to utilize the wearable technology at more precise stimulus actuation on the body [5], improving sensation variety, and portability [6]. Fabric, as another essential material that provides unique haptic sensations, plays a vital role in wearable technologies for energy harvesting, attitude sensing, and comfort evaluation [6–9]. Leveraging fabric's wearability and combining it with haptic actuators, various haptics advantages can be realized in different scenarios, such as enhancing intimacy perception [10], synchronizing senses to reflect emotions [11].

However, when designing haptic sensation in wearable technology, designers and engineers often face a common yet complex question: *"I know haptics are amazing components, but which haptic sensation should I choose, and which haptic actuator or fabric should I use to achieve my goals?"* This challenge arises primarily due to the wide range of options available for selecting appropriate actuators and fabrics, in the design of haptic sensations for wearable technologies. Each type of actuator (e.g., pneumatic silicone [12], vibration motor [13], and shape memory alloy (SMA) [14–16]) and fabric (e.g., Soft-Harsh [17, 18] or Smooth-Rough [17, 18]) generates distinct types of haptic sensations. Furthermore, each sensation type (e.g., compression [19], friction [20], stretch [21], and vibration [22, 23]) provides a unique sensory experience.

In addition, designing wearable technology often requires interdisciplinary expertise, including interaction design [24], fashion design [25], and programming [26]. This inherently complex process integrates research through design (RtD) [27] with technical implementation, often requiring collaboration between specialists from diverse fields. A key challenge lies in aligning these disciplines, such as blending haptic sensations with fabric design and engineering [10], requiring both an understanding of user sensory experiences and the ability to bridge gaps between creative design and technical feasibility [28]. Given these difficulties, previous researchers usually developed wearable toolkits to facilitate this complex design process due to the advantages of simplifying prototyping [29, 30] and demystifying abstract hardware and software concepts [31]. However, there are some existing issues: limited customization options [32], the complexity of integration [33], and poor material compatibility [25]. To address these challenges, we propose integrating haptic actuators and fabrics with different sensations into accessible toolkits, empowering interdisciplinary groups to develop innovative and practical wearable technologies for diverse user scenarios. Therefore, this paper aims to address the following questions.

- RQ1: How to design a wearable toolkit that effectively integrates different haptic sensations with fabric?
- RQ2: What are the considerations, challenges, and design space of interdisciplinary groups when prototyping a wearable toolkit that integrates haptic actuators and fabric?

We first conducted a formative study with 16 participants to discover their general collaboration challenges and expectations of wearable toolkits as our design goals. Based on that, we designed HaptiFab, a toolkit with haptic actuators and fabric integration for interdisciplinary groups to design wearable technology. HaptiFab consists of three main components: a) Haptic Generation Kit, b) Fabric Kit, and c) Design Manual to allow users to do DIY design prototypes without fully understanding the background of professional wearable technology. We conducted a five-day workshop with 30 participants to form seven interdisciplinary groups to use HaptiFab for wearable design. We used the mixed research method, including interviews, observations, and questionnaires to evaluate HaptiFab by collecting participants' experiences and perspectives on its usage. Our findings indicated that Haptifab could support varied designs, resulting in prototypes spanning functional, emotional, and educational use cases. Our findings also revealed that HaptiFab can create practical and emotionally resonant solutions while fostering collaboration by lowering technical barriers and enhancing adaptability, supporting diverse user goals. We report participants' design considerations during usage, with more design space for HaptiFab's potential. This study demonstrates the potential of haptic and fabric integration to empower designers and engineers, expanding the possibilities for wearable technology in various user scenarios. We also discuss the advantages of haptic and fabric integration in wearable technology design and provide design suggestions for future toolkits.

2 RELATED WORKS

2.1 Haptic Actuator Sensations

In the field of wearable technology, haptic sensations triggered by external stimuli include vibration [13, 22, 34, 35], compression [17, 32, 36, 37], stretch [16, 21, 35, 38–42], contractile [43], bending [44], expanding [45], and pinching [45]. Among these, three key actuation methods—compression, stretch, and vibration—are particularly significant. The proper use of haptic actuators can provide suitable sensations to meet functional needs in various scenarios, such as social interaction [46], emotional communication [47], and entertainment games [33].

Compression. The sensations of compression are commonly achieved through pneumatic actuators [12, 17, 32, 36]. Pneumatic compression can produce a range of haptic effects, from subtle to intense and intimate sensations [48]. Compared to hydraulic systems, which may pose risks of liquid leakage and equipment damage, pneumatic silicone has demonstrated its suitability for wearable applications in several studies [17, 49]. Additionally, pneumatic silicone is easy to customize [49–51]. For example, He et al. [36] use custom-molded pneumatic silicone to provide a range of haptic cues on the arm. Customizable pneumatic silicone is highly effective as a compression device, offering both safety and comfort when applied to the body [36, 48].

Stretch. In wearable technology, stretch actuators attached to the body often generate skin-stretch sensations like dragging, pinching, or twisting [10]. Shape Memory Alloy (SMA) is ideal for producing such haptic sensations by applying shear forces to stimulate the skin's deformation detection [52]. SMA is lightweight and compact, allowing for seamless integration without altering the overall shape, such as in haptic pin arrays [40, 53, 54] and fingertip-mounted skin stretch devices [21]. Additionally, their silent and flexible activation makes them widely used in inconspicuous wearable technologies, such as in medical wearable exoskeletons [44, 55] and smart fabrics that support astronauts' cardiovascular systems [56, 57].

Vibration. Vibration actuators provide immediate yet sustained haptic feedback [28, 48]. They can offer specific or symbolic sensations, making them ideal for use in wearable devices, such as emotion-based social media applications [22, 23, 46], rehabilitation monitoring garments [58], and VR-enhancing devices [59]. Hollow cup motors [60] and linear motors [61] deliver high-frequency, precise, and low-power operation. In contrast, piezoelectric motors [62] have a smaller working range, and DC motors [63, 64] often require additional mechanical transmission systems, making them less suitable for applications requiring stronger feedback. These benefits make hollow cups and linear motors particularly well-suited for wearable device designs.

2.2 Fabric Sensations and Applications

Fabrics have been extensively applied in various domains, serving as both functional and sensory components in technology and design. Prior research highlights their versatility, including artistic expression [65, 66], assistive devices [67, 68], electronic clothing [69–73], and interactive products [74]. In particular, the tactile properties of fabrics significantly influence user sensations. Jiao et al. evaluated various fabrics (e.g., cotton, nylon, and polyester blends) [75] and identified different sensations such as smooth-rough, soft-harsh, and hairy-stiff [76, 77]. Similarly, Bhömer et al. explored anisotropic fabric structures through prototyping, demonstrating their potential to enhance the skin-friendliness and comfort of wearable devices [25]. These studies illustrate the importance of fabric selection in designing wearable systems that prioritize user comfort and experience.

Beyond material properties, research has explored different fabric construction techniques for wearable design. For instance, organza fabric with a plain surface has been used to develop functional and aesthetic components in interactive wearables [78]. Origami structures have enabled dynamic adaptability in wearable systems [79], while lace constructions have been utilized for creating decorative skin inter, showcasing versatility in diverse design scenarios [80]. These studies emphasize how fabric construction techniques are important in wearable design, offering both functional and decorative potential.

In the domain of haptics, fabrics serve as passive responsive substrates [81], interacting with haptic actuators to act as "carriers" within wearable devices. These fabrics enable the delivery of haptic sensations to users while simultaneously enhancing experiences. For example, integrating haptic actuators into fabrics allows wearables to provide feedback such as contraction [82] and compression deformation [83], enriching the interaction experience. However, integrating these functionalities into adaptable wearable systems remains a complex challenge, requiring further exploration of fabric properties, haptic feedback, and user experience to fully unlock the potential of fabrics in wearable technology.

Thus, advancing wearable technology requires the effective integration of haptic sensations from both fabrics and actuators to meet diverse user needs. Our work addresses this challenge by integrating multiple fabric techniques in our toolkit to enable versatile applications across different scenarios.

2.3 Adapting Haptic Toolkits and Theoretical Design Method for Wearable Technology

In the Human-Computer Interaction (HCI) community, the development of DIY prototyping toolkits for novel wearable technology has aimed to provide low-cost, open-hardware solutions for wearable haptic interfaces [5, 30, 49, 84]. These toolkits address challenges in design, fabrication, sensing, and actuation by introducing innovative materials and workflow design [85], creating functional physical widgets and control components [86], or developing integrated hardware and firmware environments [84], thereby lowering the barrier to entry and supporting the design of different haptic sensations for various body parts [30]. For instance, Compressables-based haptic interactions on various body parts support open-ended design [31] Beyond specific use cases, toolkits of Soma design enhance body awareness, foster aesthetic appreciation, and broaden the design space for intimate wearable technologies [87]. However, current wearable toolkits have yet to adapt to the diverse needs, as most are typically designed for specific or limited contexts. This limitation becomes more pronounced in interdisciplinary collaboration, where designers and engineers frequently face obstacles. To address these interdisciplinary challenges, theoretical design methods provide a structured foundation for guiding design processes, facilitating shared goals, and fostering a unified knowledge system [88]. Various theoretical design methods [89, 90, 90, 91] have inspired our research. The Function-Behavior-Structure (FBS) model simplifies design by breaking it into function, behavior, and structure, guiding designers and engineers in defining a system's purpose and actions. Similarly, Hasso Plattner's five design thinking stages—empathizing, defining, ideating, prototyping, and testing—provide a structured framework for problem-solving [91]. However, bridging design thinking and technical principles in an interdisciplinary context remains challenging [92]. Zimmerman et al.'s framework of three types of knowledge—how, true, and real [27]—provides a foundation for selecting appropriate haptic actuators [30] and fabrics

[76], ensuring functionality and meaningful haptic experiences in wearable design. These integrated approaches help designers and engineers balance creativity with technical rigor [49], leading to innovative and practical wearable solutions.

Drawing on insights from these theoretical methods and existing literature, our goal is to develop a wearable toolkit that integrates different haptic actuators and fabrics. By leveraging these methods, the toolkit aims to help designers and engineers overcome interdisciplinary challenges and create rapid prototypes that adapt to various everyday scenarios, without requiring expertise in multiple disciplines.

3 Formative Study and Design Goals

To further explore the challenges in interdisciplinary design, we conducted a focus group with designers and engineers. Based on these findings, we identified our design goals, which played a crucial role in guiding the development of our design manual and the selection of prototypes.

3.1 Formative Study

3.1.1 Participant and Procedure. We invited 16 participants with interdisciplinary expertise in design and engineering, as well as experience in prototype development and cross-disciplinary projects. Their diverse backgrounds enabled them to offer valuable insights and feedback. To explore the challenges of interdisciplinary design, particularly in integrating haptic actuators with fabric, we organized a two-hour focus group discussion. The session included an introduction to existing HCI research on haptic sensations and tactile prototypes using fabrics in wearable technology. During the discussion, we focused on the following two key topics: the challenges designers and engineers face when collaborating on interdisciplinary design, and advice for toolkit design to support the integration of haptic actuators and fabric. Based on the discussion, we identified key challenges and proposed potential improvements to guide the development of a framework that better supports interdisciplinary design processes.

3.1.2 Findings. While participants acknowledged the importance of interdisciplinary collaboration for integrating haptic actuators and fabric, they also highlighted several challenges associated with this process. Based on their feedback, we identified the following key findings:

Communication Challenges Across Disciplines. One of the major issues is the communication barrier between designers and engineers. Designers tend to focus on user experience and aesthetics, while engineers concentrate on hardware implementation and functionality. As one Fashion Designer reflected, due to differences in professional languages and working styles, communication efficiency and accuracy are often affected. To overcome this issue, some participants suggested adopting more structured communication processes, such as design manuals and visual tools, to align interdisciplinary design requirements.

Toolkit for Integrating Different Haptic Sensations. Designers have emphasized that, in addition to ease of use, tools should support the simulation of diverse haptic sensations. Given the variety of sensations in modern products and research, it can be challenging to match specific actuators to their corresponding sensations. Effective tools would not only clarify these relationships but also enable designers to tailor haptic experiences to specific use cases and user groups. Engineers also face challenges, particularly in integrating haptic actuators into the fabric while ensuring comfort, and effectiveness, without compromising the fabric's flexibility and wearability. A well-structured toolkit categorizing various fabric types and their compatibility with haptic actuators could support engineers in making informed design decisions aligned with material properties and user needs.

Accessible and Cost-effective DIY Prototyping. Translating abstract ideas into tangible prototypes is a shared challenge for both designers and engineers, particularly when it comes to sensory feedback or physical interactions. Designers often rely on intuitive exploration and iterative adjustments, which underscores the need for simple, user-friendly prototyping tools. However, existing tools, such as haptic actuators like motors, are often difficult to integrate and have a certain level of complexity. Engineers also mentioned that they face similar difficulties in communicating complex technical solutions, highlighting the need for accessible prototyping methods that promote collaboration and innovation across disciplines. In this context, DIY-friendly, easily accessible, and cost-effective kits have proven especially valuable for fostering creativity and conducting multiple iterations of experiments.

3.2 Design Goals

Based on our literature review and formative study, we summarized a series of limitations of current wearable toolkits and the challenges of integrating haptic actuators and fabrics, including 1) Limited Customization Options, such as [32], 2) Complexity of Integration [33], 3) Poor Material Compatibility [25]. These disadvantages provide us with more insights into three design goals.

- **Wearability:** Since different body parts have varying sensitivity thresholds, the haptic sensations experienced can differ across regions. As a wearable device, our toolkit should support designs for all body parts, as mentioned in existing studies [49]. It should incorporate haptic materials that easily adapt to the shape and size of the user's body, enhancing both comfort and flexibility.
- **Adaptability:** To ensure our toolkit can meet the needs of different scenarios and accommodate specific user expectations, we proposed offering various haptic modules in different sizes and configurations. These combinations allow for diverse sensory experiences, meeting individual customization preferences.
- **Accessibility:** To make the toolkit easier for interdisciplinary groups, we aim to explore ways to reduce technical barriers for non-programmers by designing a haptic generation kit adaptable to different programming skill levels. We recommend providing diverse sensory actuators, driver modules, and clear usage guidance to enhance accessibility and meet the practical needs of designers and engineers.

4 HAPTIFAB TOOLKIT

To answer our RQs, in this paper, we developed a wearable toolkit, HaptiFab, that enables the integration of haptic actuators and fabrics, allowing designers with a single background to engage in an interdisciplinary design process. HaptiFab consists of three parts: Haptic Generation Kits (Figure.2 a), Fabric Kits (Figure.2 b), and a Design Manual (Figure.2 c). This toolkit mainly draws on insights from the haptic toolkit [31, 84] and design-centered approaches [30]. Based on our literature review, we critically reflected on the technical barriers in haptic design and the specialized knowledge required in fashion design to identify potential challenges users may encounter. Based on these reflections, we propose the following features for HaptiFab.

4.1 Toolkits Features and Components

4.1.1 Haptic Generation Kit. The Haptic Actuator Kit consists of three components: Electronic Modules, Haptic Output Actuators, and Driver and Adhesion Modules, as shown in Fig.2 a.

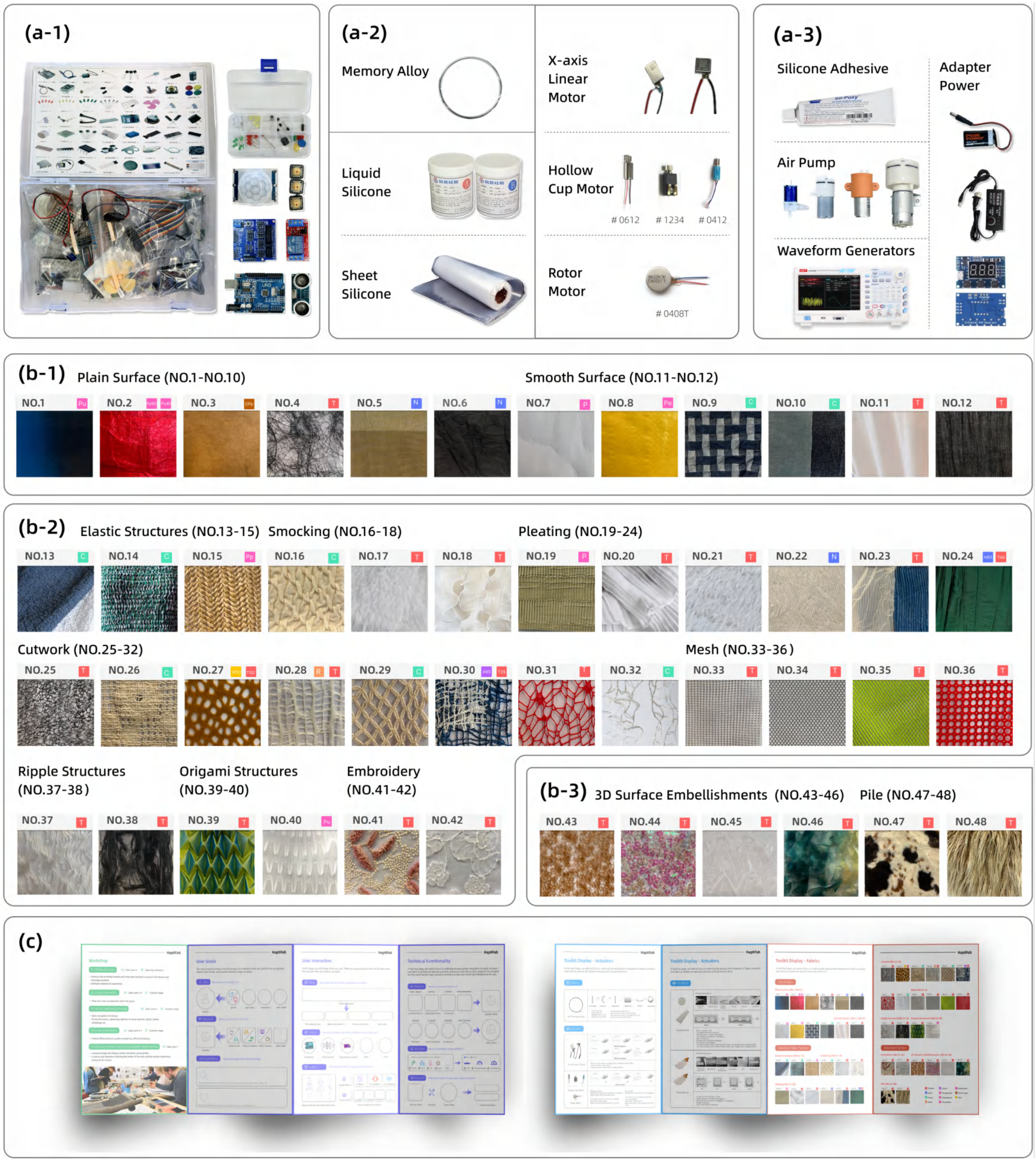

Fig. 2. HaptiFab overview. a) Haptic Generation Kit, a-1: electronic modules, a-2: output actuators, a-3: driver and adhesion modules, b) Fabric kit, b-1: Flat Surface, b-2: Structural Fabric/Surface , b-3: Decoration Surface , c) Design Manual.

Electronic Modules. The Electronic Modules are the core components for integrating wearable technology with various sensors and actuators. Users can design haptic feedback using these modules, which support both simple setups and advanced programmatic control. This design ensures accessibility for individuals of all skill levels, from beginners to those experienced with platforms like Arduino. The modules have the same control ports as standard Arduino modules, including digital I/O, VCC, and GND ports. Our toolkit provides users with both manual and programmatic control components. For users without programming experience, we recommend using button and knob modules such as the Push Button Switch. For those familiar with open-source electronic prototyping platforms like Arduino, we provide programming examples for more advanced control. Additionally, we offer a basic Arduino-compatible kit with 56 modules, covering nine sensors and various output modules, such as LEDs, microphones, relays, and PWM control modules.

Haptic Output Actuator. Based on literature review, we identified three commonly experienced haptic sensations: Compression [17, 32, 36, 48], Vibration [22, 23, 34, 46], and Stretching [35, 39, 41, 52, 93]. As illustrated in Fig.3, these sensations are commonly associated with specific haptic actuators. Based on insights from our formative study and design goals, we selected three haptic actuators for our system: Pneumatic Silicone, Vibration Motor, and Shape Memory Alloy (SMA) based on their ability to produce these desired sensations effectively. Detailed parameters are provided in Appendix A.2. These actuators were selected for their ability to offer diverse haptic feedback, adaptability across various wearable contexts, low cost, and DIY-friendly implementation for interdisciplinary groups, making them ideal for our study.

Research	Haptic Actuator	Haptic Sensation					Wearing Position	Fields of Application
		Stretch	Compress	Vibration	Friction	Num		
Squeezeback [17]	Pneumatic Silicon		●			1	Full body	Gaming, Education, Food Testing
PneuHaptic [32]	Pneumatic Silicon		●			1	Arm	Remote Communication
PneuSleeve [36]	Pneumatic Silicon		●			1	Wrist, Arm	Gaming, Remote Communication
HYFAR [37]	Pneumatic Latex		●			1	Chest, Arms	VR/AR
TaSST [28]	Vibration Motor			●		1	Arm	Emotions Expressions
MouseClicker [34]	Vibration Motor			●		1	Hand	Medical Care
Rice Haptic Rocker [13]	Vibration Motor	●				1	Arm	Navigation
SqueezeBands [21]	SMA	●				1	Hand	Remote Communication
Sprout I/O [35]	SMA				●	1	Full body	Wearable
Sobee-SMA [40]	SMA	●				2	Arm	Medical Care
Soft Haptic Glove [41]	SMA	●				1	Hand	VR
ANISMA [42]	SMA	●				1	Full body	Coding

Fig. 3. Physical Sensation Corresponding to Different Haptic Actuators

Pneumatic silicone materials include both liquid silicone and sheet silicone, offering various parameters for selection by designers and engineers. Our study used liquid silicone (Shenzhen Guoyuan Technology Co., Ltd.), with hardness grades T00 and T05. Silicone sheets are relatively stiffer and less elastic than liquid silicone, the thickness of the silicone sheets ranges from 0.3 mm to 1.0 mm (Shenzhen Xinyin Environmental Rubber Product Co., Ltd.). As the hardness or thickness increases, a greater volume of air is required to deform the silicone. Users can create a variety of compound shapes through techniques, such as surface curving and texture changes [36, 50, 51], as illustrated in Fig.4. Liquid silicone is very soft and highly flexible, but it requires fixed molds for production to form a unified structure.

Vibration motors include an X-axis Linear Motor (1016 motor, ACC®), which can be adjusted for frequency, amplitude, and duration. For the convenience of more designers who aren't familiar with the motor's parameters, we selected a different rotor motor structure(0408T, Shenzhen Kuanyang Intelligent Technology Co., Ltd.) and Hollow Cup Motor (0412, Sanyo Japan massage motor; 0612 and 1234, Shenzhen Kuanyang Intelligent Technology Co., Ltd.) that allows for speed adjustment, as illustrated in Fig. 4. The Hollow Cup Motor adjusts speed and torque by controlling the current and the stator's magnetic field. The Rotor Motor generates rotation by interacting with the current and the rotor's magnetic field. The X-axis Linear Motor drives linear motion directly via electromagnetic force. These motors typically require Pulse Width Modulation (PWM), a frequency converter, or a speed controller for effective operation. To assist designers who may not be familiar with motor parameters, we provide arbitrary waveform generators for flexibility and accessibility.

Shape Memory Alloy (SMA010, Lanzhou Seemine Keli Advanced Material Co., Ltd) is commonly utilized in two driving methods widely adopted today: electrical deformation and heating deformation. We selected a two-way shape memory alloy without pre-formed shapes, as illustrated in Fig. 4, allowing flexible and customizable applications. Mechanical testing indicates a 4.5% length shrinkage after energization. Considering the heat generated by the SMA, we have equipped it with a soft silicon tube of appropriate size for the SMA [10] to provide insulation.

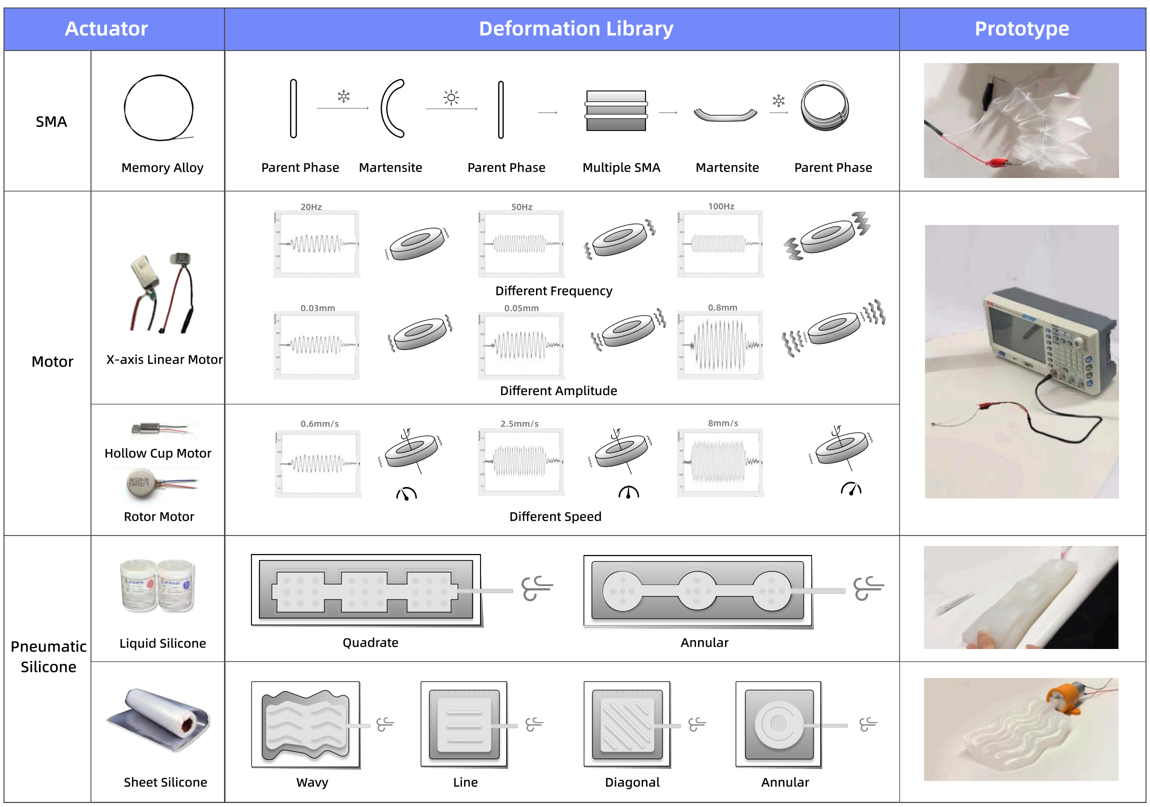

Fig. 4. Actuator library showcasing SMA, Motor, and Pneumatic Silicone

Driver and Adhesion Modules. Our toolkit also provides Driver and Adhesion Modules, which assist designers and engineers in bonding and driving haptic actuators. All output actuators are designed to be compatible with Arduino, allowing for seamless integration and control. The vibration motor's data can be modulated using a PWM (Pulse Width Modulation) signal. Utilizing arbitrary waveform generators (UTG4162A Waveform Generator, UNI-T®) enables designers to adjust frequency, amplitude, and duration without requiring programming skills. In addition, the SMA can be stretched using an electric adapter, making it user-friendly for non-technical users. The pneumatic silicone can be inflated with an air pump, available in 12V, 24V, and 36V options. Each pump is equipped with solenoid valves and an air pressure sensor. For liquid silicone, the actuator typically needs to be set for about 45 minutes, while sheet silicone requires bonding with a specialized silicone adhesive (Sil-Poxy, Smooth-On®). Detailed parameters are provided in Appendix A.2.

4.1.2 Fabric Kit. In the context of wearable technology, fabrics that come into direct contact with the skin. The haptic properties of the fabric are important for clothing comfort [77] parameters such as pressure and friction forces are important for sensory stimuli and haptic feel [94]. Recognizing the importance of these factors, we offer 48 different fabrics, including polyester, wool, and cotton, to meet a wide range of usage scenarios [11], ensuring comprehensive evaluation and enhanced comfort in wearable applications, as illustrated in Fig.2 b, and the detailed components as shown in Appendix B.1 B.2. Most of these materials are produced through woven and knitted processes, with some undergoing special post-processing techniques such as skeletonization, pleating, and embroidery. Woven fabrics offer high stability and are less prone to deformation, while knitted fabrics provide good elasticity and can be easily shaped [95]. We also provide fabric samples of varying lengths and sizes, encouraging customization using knitting machines and looms to support designs tailored for different body parts, to improve wearability and adaptability. The selection of fabrics considers the diverse haptic sensations associated with different construction methods and materials, such as the roughness of irregular textures or the prickly feel of fine pinpoints [77]. These variations aid users in better categorization and differentiation. We classify Fabric Construction Techniques into three categories based on their characteristics and structural properties:

- Flat Surface Techniques: Focused on smooth and minimally processed fabrics, such as Plain Surfaces (No.1-10) and Smooth Surfaces (No.11-12).
- Structural Fabric Techniques: Enhancing physical structure and functionality, including Ripple Structures (No.13-NO.14), Origami (No.15-16), Elastic Structures (No.17-19), Smocking (No.20-22), Pleating (No.23-28), Mesh (No.29-32), and Cutwork (No.33-40).
- Surface Decoration Techniques: Adding visual and tactile embellishments, such as Embroidery (No.41-42), Pile (No.43-44), and 3D Surface Embellishments (No.45-48).

4.1.3 Design Manual. We also provide a design manual to guide users through the prototyping process from a design discipline perspective, drawing on the 5 Phases of Design Thinking [96], the FBS Model [90], and RtD [27], as illustrated in Fig.2 c. This manual aids designers and engineers in constructing the 3 phases: User Goals, User Interaction, and Technical Functionality (material-structure-function). By following the step-by-step guide, we help designers and engineers incorporate unfamiliar materials and address challenges such as inconsistent foundations, terminology variations, and methodological differences [97].

User Goals (User-Scenario-Expectations). The first phase emphasizes understanding the target user groups, observing their needs, and analyzing relevant usage scenarios. This phase focuses on understanding the users' pain points and translating them into clear user goals. The design manual assists in visualizing user journeys and scenarios

[28, 39, 98], gathered from interviews and field observations. This structured approach ensures that the design process remains user-centered from the very beginning.

User Interaction (Input-Process-Output). User interaction refers to how users engage with the toolkit, encompassing their inputs, the processes triggered, and the resulting outputs or feedback. Designers can map how the toolkit dynamically responds to various inputs, such as physiological data [5], behavioral patterns [48], or manual commands [74], ensuring an intuitive and adaptive interaction process [33]. This approach aligns the output with user needs, fostering a seamless and engaging experience.

Technical Functionality (Material-Structure-Function). Defining technical functionality requires integrating haptic actuators with fabric to achieve the desired outcomes. This involves evaluating material interactions and properties (e.g., flexibility, durability) that impact the design. The structure must support the intended function, ensuring haptic actuators deliver precise and meaningful feedback. Adjusting material parameters to meet various haptic feedback requirements is important for a cohesive and satisfying user experience. This phase ties the entire design together by ensuring that the physical and technical aspects [76] align with user expectations and interaction goals.

5 WORKSHOP

To evaluate how participants interact with HaptiFab, we conducted a workshop study with 30 participants in seven interdisciplinary groups. We utilized mixed research methods to answer our research questions by 1) observing the prototype design process by each group, 2) gathering perceptions through focus group interviews, and 3) analyzing user questionnaires.

5.1 Participants and Procedure

We posted our recruitment on social platforms for ten days, receiving 182 applications. Participants were selected based on: (1) availability to attend the entire onsite workshop, (2) a portfolio demonstrating basic knowledge of haptics or fabrics, and (3) research focus on a relevant field (e.g., fashion design, interaction design, or engineering) without dual expertise in design and engineering, but with proven ability to produce comprehensive interaction design work.

We recruited 30 participants (7 males, 23 females), aged 19 to 37 (M = 24.07, SD = 3.87), as shown in Table 1. Most were undergraduate and graduate students in China, with some international students. All participants volunteered their time and received certificates after the final presentation. During the 5-day workshop, participants formed interdisciplinary groups to use HaptiFab for designing and developing interactive prototypes incorporating haptic fabrics. We selected 11 workshop assistants from our lab, all with relevant research experience, and provided technical support. We also provided pre-training to ensure workshop assistants were familiar with HaptiFab's techniques and research objectives before the workshop. During the workshop, these assistants joined various groups to offer technical support.

5.1.1 *Opening Ceremony.*

The lab director introduced the lab's research on wearable technology to welcome participants. The workshop organizer (first author) then detailed this workshop's specific goals and research content, providing examples of possible usage scenarios to guide participants' thinking. We also held ice-breaking activities to facilitate group formation, resulting in seven groups of 4-5 people, each supported by 1–2 moderators. The organizer then introduced the workshop technologies, including pneumatic silicone prototyping, vibration motors, and SMA applications.

Table 1. Participants' Demographic information

Group	Participants	Gender	Age	Education	Field of Study
G1	P1	F	26	Postgraduate	Human Factors Engineering
	P2	F	21	Undergraduate	Engineering Design
	P3	F	20	Undergraduate	Landscape Architecture
	P4	F	24	Postgraduate	Industrial Engineering
G2	P5	F	22	Undergraduate	Entertainment Technology
	P6	F	26	Postgraduate	AI Analysis of Electrocardiograms
	P7	M	21	Undergraduate	Systems Engineering
	P8	F	21	Undergraduate	Product Design
G3	P9	F	25	Postgraduate	Interaction Design
	P10	M	23	Postgraduate	Industrial Engineering
	P11	F	22	Undergraduate	Fashion Accessories Design
	P12	F	37	Postgraduate	Communications Design
G4	P13	M	26	Postgraduate	Intelligent Manufacturing
	P14	M	24	Postgraduate	Textile Technology
	P15	F	29	Postgraduate	Fashion Design
	P16	F	22	Undergraduate	Interaction Design
G5	P17	F	22	Postgraduate	Industrial Design
	P18	M	24	Postgraduate	Electronic Information
	P19	F	29	Postgraduate	Digital Intelligence and Fashion
	P20	F	31	Postgraduate	Fashion Design
G6	P21	M	23	Postgraduate	Industrial Design
	P22	F	25	Postgraduate	Industrial Design
	P23	F	20	Undergraduate	Fashion Design and Engineering
	P24	F	20	Undergraduate	Interaction Design
	P25	F	22	Undergraduate	Interaction Design
G7	P26	M	23	Postgraduate	Art and Technology
	P27	F	28	Postgraduate	Design and Technology
	P28	F	21	Undergraduate	Apparel Engineering
	P29	F	26	Postgraduate	Textile Design
	P30	F	19	Undergraduate	Digital Media Arts

5.1.2 Prototype Making. After the opening ceremony, each group began their five-day design work, with workshop assistants regularly checking progress and providing technical guidance. On the third day, we held an offline mid-term exchange meeting where each group presented their design prototypes, focusing on application scenarios and technologies used. The lab director and research team conducted question-answer sessions with each group. In the following three days, groups refined their designs based on feedback, conducted tests, and optimized prototype performance. During the workshop process, we also observed participants' behavior, which focused mainly on the initial practical strategies of the participants, the mistakes they made, and the solutions they used during interactions with Haptifab. Two researchers took photos/screenshots, and wrote field notes, the entire course process for subsequent analysis.

Table 2. Prototypes Description

	Group	Thematic	Haptic Actuator	Description
Functional Wearables	G1	HarmonicWeave (Fig.5 a)	Sheet and Liquid Silicone, X-axis Linear Motor, SMA	The device uses pneumatic silicone and vibrating motors to adjust vocal behavior. It incorporates a memory alloy to affect the opening and closing of the chest flower to assist in vocalization.
	G5	Smart Navigation Wristband (Fig.5 e)	Sheet Silicone	The pneumatic silicone smart wristband provides haptic navigation for both general users and those with sensory impairments.
Self-healing Wearables	G2	ViBreathe (Fig.5 b)	Vibration Motors	This design uses rhythmic haptic vibrations on the arms to guide users through synchronized breathing, enhancing meditation and relaxation.
	G4	HUG BANK – Portable Hug (Fig.5 d)	Sheet Silicone	This project turns clothing into an interactive medium, simulating hugs with an internal air pump system embedded in the fabric. Sensors trigger and regulate hug intensity in real time, offering therapeutic comfort.
	G6	Marine Haptic Intelligent System (Fig.5 f)	Vibration motors, Sheet and Liquid Silicone	The design simulates the feeling of waves and sand through a combination of modular fabrics and pneumatic silicone, allowing city dwellers to feel the joy of a beach vacation even in their busy lives.
	G7	ZenTouch (Fig.5 g)	Vibration motors	The design uses vibrating motors to provide a gentle haptic sensation to provide emotional and physical interaction as well as spiritual solace for a new generation of religious believers.
Educational Wearables	G3	Mare Tactus (Fig.5 c)	Sheet Silicone	The design combines Sheet Silicone and fabric with multi-dimensional spatial interactions to create haptic resonance with both the positive and negative aspects of the ocean, fostering a deeper connection with the marine environment in public exhibitions.

5.1.3 Final Presentation and Interviews. On the fifth day of the workshop, we held a three-hour closing ceremony to facilitate mutual learning among participants. As shown in Table.2, each group presented their projects, detailing design rationale, technical specifics, and usage methodologies. We finally asked each participant to fill out the User Experience Questionnaire (UEQ) [99] utilizing a 7-point Likert scale and conduct focus group interviews with each group. Each focus group interview in Chinese lasted about 60 minutes and was audio-recorded with participants' content (See Appendix :interview$_{q}uestions$).

5.2 Data Collection and Data Analysis

We utilized mixed research methods to analyze data within this study. We first conducted a quantitative analysis of the UEQ resultsssess participants' actual usability experiences of HaptiFab, focusing on its pragmatic and hedonic qualities of haptic technologies and fabric materials. We then use the qualitative method for focus group interviews and field notes through thematic analysis [100]. Two researchers initially reviewed the field data (prototypes, images, and presentation slides) and interview transcriptions for accuracy. After data cleaning, two researchers started independently coding and developed an initial set of codes to analyze the data. For the field notes analysis, we focused on practice-based behaviors and used words or phrases to describe them as code. This process involved several rounds of discussion to reach agreements and grouped similar codes into clusters. They then identified emerging common themes with internal connections and finally generated themes related to toolkit experiences using a collaborative affinity mapping approach [101]. Any disagreements during coding were resolved through joint discussions and consultation with an expert (the third author) until a consensus was reached.

6 FINDINGS

Our findings highlight that HaptiFab (1) supports a variety of design purposes effectively, (2) is both efficient and easy to use, and (3) is flexible enough to accommodate different design spaces. We also provide detailed insights into participants' perceptions of usage, material preferences, and interaction modalities when using HaptiFab.

6.1 Varied Purposes of Participants' Prototypes with HaptiFab

We generally found seven interdisciplinary groups used HaptiFab to create diverse and multifunctional wearable designs, each with unique themes. Based on the scenarios they designed, we categorized their prototypes into three distinct groups (see Table 2): Functional Wearables (G1, G5), Self-Healing Applications (G2, G4, G6, G7), and Educational Exhibits (G3).

Fig. 5. The prototypes made in the workshop. a) Harmonic Weave, b) ViBreathe, c) Mare Tactus, d) HUG BANK-Portable Hug, e) Smart Navigation Wristband, f) Marine Haptic Intelligent System, g) ZenTouch.

Two groups (G1 and G5) developed their prototypes with a function-oriented approach to improve the user experience by providing specific features. For example, G1 developed HarmonicWeave (Fig. 5a), a tool to monitor breathing during singing to enhance the user's vocal performance. They integrated knitted fabric with a sheet and liquid silicone deformation, enabling precise control over the chest and diaphragm. Additionally, they attached an X-axis linear motor with the larynx and dynamically bloomed floral pattern style SMAs, with fabric wrapped, to provide real-time vibrations corresponding to vocal frequencies. Another group, G5, created a Smart Navigation Wristband designed for individuals with sensory limitations, utilizing compressed feedback for the navigation process (Fig. 5 e). Their wristband indicates left or right turns through inflation and deflation of sheet silicone on the corresponding side, with the frequency increasing as the turn approaches to enhance the alert effect. They then customized a knitted wristband using a deformation-capable knitting machine to accommodate and integrate the pneumatic seamlessly within both silicone designs.

We were surprised to find that more than half of the groups focused on users' emotional status. They use Haptifab to design self-healing applications (G2, G4, G6, G7). For instance, G2 features a sleeve designed to assist users in synchronized breathing training (Fig. 5 b). Their design utilizes five 0408T rotor motors and stretchable and translucent wave yarn to create a coordinated vibration ensemble, stitched onto a stable ice sleeve for enhanced comfort and durability. G4 made the HUG BANK, a portable device simulating hug interactions to comfort users facing loneliness and anxiety (Fig. 5 d). This design also features a skin-friendly cotton inner layer for comfort and a rigid textured woven outer layer for style and controlled deformation. There is a sheet of silicone (0.5mm outer, 0.3mm inner) that uses COMSOL simulations to map pressure to air pump inputs, creating a realistic hugging experience. G6 also focuses on enhancing user experiences. They developed the Marine Haptic Neckband to provide urban dwellers with brief escapes from busy lives by simulating the sensations of waves and sand, evoking a fragmented vacation experience (Fig. 5 f). They used circular pneumatic silicone to simulate the rippling motion of waves, with four modular fabric components to simulate the tactile sensations of sand, home, and other textures. G7's design is more special. Their Zen Touch project aims to create a haptic metaphysical feedback system for Chinese Gen-Z inspired by traditional religious customs (Fig. 5 g). Their system integrates spiritual and calming practices from Chinese culture, particularly the Buddhist and Taoist beiyun (a decorative element of prayer beads symbolizing respect when draped on the back). Users can initiate blessings with hands clasped in prayer, or the system's heart rate sensor triggers a vibration on the back during moments of anxiety. The design features No.43 3D surface embellishments for a modern touch, while No.15, No.26, and No.29 create a rough, rustic feel symbolizing the strength of calloused hands. No.36's regular mesh reflects traditional bracelet elements, and smooth No.2 and No.7 materials are used on the back for comfort. These fabrics are sewn together to represent the five symbolic motifs of Fu, Lu, Shou, Xi, and Cai [1].

Moreover, we also found that Haptifab supports users in designing wearables for educational exhibits. G3 developed a neck-worn device inspired by an aquarium experience (Fig. 5 c). They aim to address the limited interactivity in traditional aquarium exhibits, they utilized cutwork (mesh) fabric with a rough haptic sensation, combined with airbags featuring circular, linear air channels (0.5mm outer, 0.3mm inner) to create a sense of pressure. This design evokes negative haptic experiences, metaphorically representing the environmental stress and 'suffocation' caused by marine pollution, to heighten awareness of the ocean pollution crisis.

[1] In Chinese traditional culture, Fu (福) represents blessings and good fortune, Lu (禄) symbolizes power and success, Shou (寿) signifies longevity and health, Xi (喜) means joy and happiness, and Cai (财) has the connotation of wealth and fortune[102]. Together, these concepts reflect traditional values of a prosperous and fulfilling life in Chinese tradition.

6.2 Examining Participants' Exploration of HaptiFab

We observed that participants made diverse, practical decisions when using HaptiFab and selecting various components. In this section, we will discuss how users perceive these sensations and adapt to different usage contexts with three main considerations.

6.2.1 Goals Consideration. Guided by the design manual, participants usually first identified their goals, including target user and usage scenario. They then conducted detailed research on the expectations of these groups before integrating the haptic actuators and fabrics. For example, P1 mentioned, *"...For some beginners or people with limited knowledge of vocal techniques, it is difficult to control... the vibration of the larynx and the breathing of the diaphragm. Overall...we selected the main parts of the human body that are most likely to affect singing..."*

After defining their user and scenario in the *user goals* based on the design manual, participants developed specific expectations for their prototype, including both functional and experiential sensation aspects. For instance, G1 outlined functional expectations, with P4 noting: *"...Therefore, we expect to...create haptic synchronized with the song, allowing users to feel the vibrations in their larynx to determine whether it matches the haptic component. If they do not match, it is obvious that the user's vocalization is incorrect..."* Some participants also emphasized expectations of experiential sensation for their prototypes. For example, G7 aimed to create a sense of comfort or reassurance. For example, P26 stated: *"...In traditional blessings, the gods may not respond to you, but this smart product can give you a response..."* Others, such as G4, envisioned the prototype offering a more expansive feedback experience. P15, one of the group members mentioned that: *"...When we think of a hug, we tend to think of the strength of the hug... or a feeling of being wrapped up, which is more expansive, and it can provide a strong sense of feedback..."* Participants identified target user groups and usage scenarios to conduct preliminary design research, aligning their designs with both functional needs and experiential sensations, which facilitated the creation of effective prototypes later in the process.

6.2.2 Interaction Consideration. Participants in the focus group considered several aspects of user interaction considerations with wearable prototypes, including technical integration, body adaptability, sensory feedback, and cultural factors.

Integration Techniques and Process. In designing interactive prototypes, participants often incorporated electronic modules to trigger haptic interactions. The Arduino kits provided by HaptiFab played a crucial role in this process, and combined with the design manual, they helped the interdisciplinary groups refine their prototypes while exploring additional possibilities. For example, G1 used real-time IMU monitoring on the chest area to control the SMA within petal-like structures (Fig. 6 a). G7 employed a heart rate sensor to trigger vibration motors for soothing effects. In G4's design, the aim was to replicate the sensation of a hug. Therefore, P14 gathered user input on palm pressure and used finite element analysis to extract the pressure distribution of a real hug, which was then applied to their prototype for greater haptic realism (Fig. 6 d).

Wearability and Adaptability in Different Body Parts. As a full-body wearable toolkit, HaptiFab demonstrated significant wearability and adaptability across various body parts. Participants considered factors like user interaction needs, sensitivity thresholds, and body posture when selecting locations for haptic sensations (P9, P18, P22). For instance, G6's prototype focused on the sensation of submersion in seawater. P22 explained that the neck's high sensitivity was critical to their design. Precise pneumatic sensations and fabric textures mimicked seawater moving against the neck, enhancing immersion. G5's design also took sensitivity thresholds into account, focusing on the wrist, which has a lower threshold and is more responsive to directional cues. P17 mentioned, *"...The sensitivity of the wrist is not that high... our prototype initially featured a single ring-shaped airbag that would indicate directionality from left to right, but we found that the wrist's sensitivity wasn't clear enough..."* P17 also noted that factors such as age and gender needed to be considered in the design process. In addition, the design incorporates inspiration from cultural contexts. For example, G3's design, inspired by traditional Chinese medicine, aimed to evoke feelings of suffocation and entrapment, with a particular focus on the neck due to its sensitivity and symbolic association with breath control. Pneumatic silicone and fabric were used to simulate the sensation of being trapped in a fishing net, with the *'Fengchi'* [2] acupoint was precisely stimulated. By inflating the silicone material around the 'Fengchi', G3's design created a tight feeling, intensifying the discomfort (P10).

Material Sensory Characteristics. Participants expressed high satisfaction with the sensory diversity offered by both the haptic and fabric components of HaptiFab (P7, P9, P28, P30). They noted that the prototypes met their initial expectations for sensory feedback (P7, P28). For instance, P17 described the design of a navigation wristband for cyclists: *"...The airbag provides a gentler reminder, while vibration might be more direct...Our prototype...is not designed for emergency alerts, but rather for guiding navigation, such as a 100-meter advance notice before a turn..."* (Fig. 6 e). This feedback highlighted the effectiveness of using different materials and haptic technologies to cater to the specific needs of users and interaction contexts. In conclusion, we found that integrating techniques into the design process shaped the prototype's outcome, meeting diverse user needs with immersive haptic feedback.

6.2.3 Technical Functionality Consideration. Our participants emphasized the importance of integrating haptic actuators and fabric to ensure the structure supports the intended function and provides accurate feedback.

Haptic Actuator Selection. When using HaptiFab to create wearable prototypes, our participants carefully selected haptic actuators based on several key factors. *Pneumatic silicone* was the most frequently used material, valued for its large-area force sensations (P15) and soft (P2), skin-adhering surface (P17, P18). P2 highlighted its suitability for close body contact, with its adaptable volume and shape-enhancing design flexibility and applications [51]. However, factors such as air pathway design, pressure application, and material thickness affect performance (P4, P17). For instance, P3 observed that a 0.3 mm sheet of silicone was prone to bursting, while P4 recommended liquid silicone glue for stronger bonding. These challenges require iterative prototyping to optimize designs. *Shape Memory Alloy (SMA)* was praised by participants for its stretchable properties and ability to achieve multi-angle deformation (P2). While its range of deformation changes is less pronounced than that of other devices. P3 noted SMA's strong embedding properties, which allow it to be fully wrapped, making it ideal for wearable devices in space-limited designs [10]. Participants praised the *vibration motors* for their precision and timely sensation, providing direct haptic sensations (P26). Their small size and strong vibrations make them ideal for wearable designs requiring discretion and responsiveness. However, as P17 observed *"...The small size of motors requires proximity to the skin for effective sensation, limiting their use in designs with larger direct contact surfaces..."* To address this limitation, the impact of the motor can be enhanced through vibration synthesis. Several motors can be combined to synthesize a haptic sensation (P18). This was demonstrated in G2's design, where an array of motors expanded the range of skin deformation, as shown in Fig. 6 b.

Aesthetics and Integration with Structure. Participants integrated aesthetics and symbolic meanings to align with *User Goals*. Some symbolic meanings come from fabric, G3 used mesh fabrics and airbags to symbolize ocean pollution,

[2]FengChi (风池)refers to an acupoint located in the hollow at the base of the skull just below the hairline, is significant in Chinese medicine culture. Stimulating it can relieve headaches and relax neck muscles, often accompanied by a sensation of soreness or mild pain.

creating a rough, trapped sensation around the neck (Fig. 6 c). Similarly, G7 used goldfish-shaped fabric with symbolic colors representing fortune and longevity, combining cultural metaphors with visual appeal. Some of the symbolic meanings come from haptic actuators, G1 used SMA and mesh to create a flower shape, symbolizing chest cavity movement during breathing and enriching the sensory experience. G4 uses pneumatic silicone shaped embracing hands to symbolize a hug. Another key aesthetic consideration was integrating haptic actuators seamlessly within the fabric. Most participants preferred the actuators to be fully wrapped (G1, G2, G4, G5, G7), and G1 concealed the SMA within petal-like structures that blossomed dynamically. Some preferred partial wrapping (G3, G6). G6 used modular designs with partial wrapping, allowing users to swap and customize haptic sensations, such as flocked fabric evoking a rough beach texture or looped velour providing a plush feel (P23).

Fig. 6. These group figures provide a detailed explanation of the selection of materials, haptic actuators, and haptic sensations from each group's prototype. From a) to g), each single figure corresponds to Group 1 to Group 7, offering a visualized explanation.

6.3 Effective Wearable Design Process Powered by HaptiFab

HaptiFab is adaptable, accessible, and user-friendly for interdisciplinary groups, as demonstrated through a mixed-method analysis.

6.3.1 The UEQ Result of HaptiFab. In this stage, the UEQ evaluates the user experience of HaptiFab. We used the official UEQ Data Analysis Tool Version 12 [103] to convert the 1-7 scale values to a range of -3 to $+3$, where $+3$ indicates the most positive and -3 the most negative value. We assessed the reliability of the data collected from the 26 items in UEQ, obtaining a Cronbach's α of 0.949, which indicates high internal consistency. We also compared the UEQ results of HaptiFab with benchmark data from 468 studies concerning different products, and the findings are presented in the bar chart shown in Fig. 7.

For the six dimensions, the questionnaire in HaptiFab scored highly in ‘Attractiveness’ (M = 1.872, SD = 0.824) and ‘Stimulation’ (M = 1.792, SD = 0.974) achieving an *Excellent* comparison to the benchmark and significantly supporting prototype creation. Meanwhile, ‘Perspicuity’ (M = 1.367, SD = 1.096), ‘Efficiency’ (M = 1.45, SD = 0.95), and ‘Dependability’ (M = 1.433, SD = 0.858) performed *Above Average* comparisons to the benchmark, helping interdisciplinary groups lower learning barriers and prototype efficiently. Since HaptiFab builds on recognized haptic sensations, the results for Novelty (M = 1.475, SD = 1.075) demonstrated a *Good* performance compared to the benchmark. These findings are consistent with interview results, discussed later.

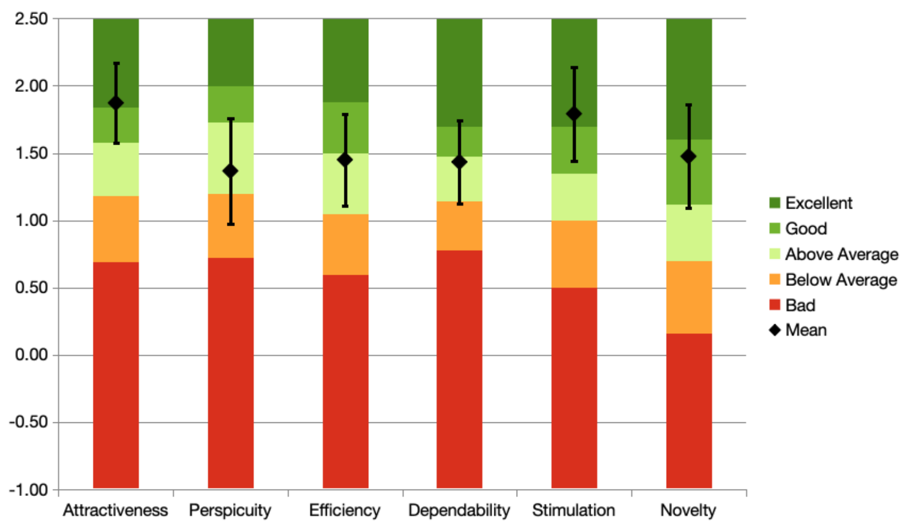

Fig. 7. Comparison of HaptiFab Results with Benchmark Data of UEQ

6.3.2 Lowering Barriers in Interdisciplinary Context. During our focus group interview, participants praised HaptiFab for empowering them to create innovative HCI prototypes (P18) and facilitating collaboration in interdisciplinary contexts (P1, P15). For example, P27 praised the prototypes provided, stating: *"...It is easy to use Arduino to adjust the rotor motor’s accuracy and comfort..."* and P18 mentioned that during the developing process, *"...I think it’s okay, it’s just that the ones (HaptiFab) that are prepared are also quite easy to learn, it’s just that they’re not very complicated either..."*.

Also, our participants noted that the design manual was highlighted as a valuable resource to overcome difficulties, which helped them refine design ideas and select suitable haptic actuators and fabrics (P15, P17, P23). The UEQ result also proves ‘not understandable/understandable’ (M = 1.733, SD = 1.258), ‘difficult to learn/easy to learn’ (M = 1.9, SD = 1.185), ‘unfriendly/friendly’ (M = 2.067, SD = 0.98). These results highlight the manual’s role in aligning group members’ perspectives, fostering a shared vision between designers and engineers, and enhancing usability and collaboration. However, some participants indeed shared their vision for better HaptiFab’s iteration, such as providing more detailed explanations about fabrics and separating programming and non-programming tools into two distinct sets (P4). For instance, P9 stated that: *"...I hope to see more technical information about fabric in the design manual...For example, can I weave different fabrics together to create a new form?"*. These insights offer actionable directions as future work to further enhance HaptiFab’s adaptability and accessibility.

6.4 Potential Design Spaces and Future Directios with HaptiFab

During the workshop, participants brainstormed various meaningful ideas, we summarized insights to identify three key design areas for HaptiFab: Emotional Expression Design, Augmented Design, and Therapeutic and Assistive Design.

6.4.1 Emotional Expression Design. Participants highlighted the potential for combining haptic actuators with fabric to create more emotionally resonant experiences (P11, P13, P16). P13 observed: *"...Clothing is like a second skin for humans, and the future trend of clothing will undoubtedly be greater intelligence. If people can interact with their second skin daily, it would indeed be a significant step toward the next stage of smart innovation..."* This aligns with the findings of Kim et al. [10], and G4 further noted that pneumatic silicone could effectively convey the intimacy of a remote hug, offering a more tactile, emotional connection. P16 also remarked: *"...I think this kind of haptic interaction can establish a good connection with emotional expression, which should also inspire many explorations in emotional design..."* Building on this, P6, integrating her professional background, proposed using haptic technology to simulate the heartbeat of deceased loved ones or pets, addressing the limitations of current electrocardiograms (ECGs), which only provide visual feedback. P14 underscored this potential by noting: *"Static clothing conveys little to no information, but with certain technologies, such as vibrations, it can transmit some amount of information...or sensations."* P19 also pointed out the power of haptic adding on Static textile materials such as clothing to give the user a sense of security against the body, *"...So I think that fabric materials themselves have certain advantages, but the problem is that because they are static, they stay there quietly, and then when they have a more active brake. The braking mechanism may make it more vital, and it will be like many things breathing..."* These insights highlight haptic technology's potential in advancing emotional expression design.

6.4.2 Augmented Design. We also found that Haptics, as an actuator, can be well integrated with fabrics to enable augmented design. P15 mentioned that: *" Generally, fabrics are static and do not make you feel any interaction or actively provide force. However, with haptics...you can perceive it as if it were a living entity...giving you feedback that feels as though it has emotions or a sense of life."* Additionally, users have envisioned various applications of HaptiFab for augmented design. P18 and P23 believe that wearable devices based on VR games can augment human sensations and enhance immersion. In the future, wearable devices could render haptic data to synchronize with game experiences, as noted by Han et al. (2023) [104]. Beyond gaming, P9 suggests that combining haptic technology with fabric is well-suited for inclusive design to augment human ability:

> *"...We want to create this museum because many current museum displays, like touchscreens, are flat and difficult for visually impaired visitors to understand... We hope the design can be more inclusive...can help them interact with the surroundings in museums, galleries, cinemas, and other public spaces, making these environments more accessible..."*

Similarly, P12 proposed using pneumatic silicone in clothing to develop safety-focused augmented designs, such as fall-prevention solutions for the elderly [105] or protective gear for skiers during training. These examples demonstrate how integrating haptic technology with fabric can augment practical solutions and benefit society.

6.4.3 Therapeutic and Assistive Design. Beyond wearables, participants envisioned using these HaptiFabs in therapeutic and assistive contexts. For example, P14 discussed using SMA in medical devices like guidewires and stents. Additionally, pneumatic silicone could be applied in corrective seating materials, while vibration motors could aid in posture correction (P25) or guide breathing exercises (P7). By combining pneumatic silicone with rigid materials, P14 proposed haptic robots for precise grip force measurement and weight-bearing. P17 further suggested that SMA could serve as actuators for soft robotics, expanding their functionality in both medical and industrial applications.

7 DISCUSSION

7.1 Enhancing Adaptability and Creative Comparing with Other Toolkits

In this study, we presented HaptiFab, a toolkit integrating haptic actuators and fabric, to explore how these two valuable components could benefit interdisciplinary group design wearable technology. Workshop insights show that HaptiFab stands out from previous wearable tech toolkits because of its integrated haptic actuators and driven methods that have been widely discussed in recent years within the field of HCI research [10, 49, 51]. HaptiFab provides considerable adaptability, enabling designers and engineers to tailor prototypes to diverse scenarios, user expectations, and data inputs. Compared to the fixed hardware modules of TactorBots [106], HaptiFab supports a broader range of wearable forms and areas, offering diverse haptic metaphors and expectations. It also provides more actuator options than compressables [49], with a DIY-friendly design enabling iterative customization of haptic outputs, sensory feedback, and user experiences. Unlike SleevIO [107], where fabric serves only as a 'substrate', the function of fabric in our toolkit is not only to provide a soft and comfortable wearable cover layer but also to enable users to adapt to diverse scenarios and explore broader design possibilities. To support interdisciplinary design, our manual enhances the O&O framework (Empathize-Define-Ideate-Prototype-Test) with intuitive, detailed solutions to methodological differences [97], helping groups align their vision during prototype development. We provide clear guidance for merging technical and design perspectives through a design manual combining design thinking and HCI principles [27]. This approach enables participants to use HaptiFab for hands-on DIY creation, applying the RtD method to uncover new insights into integrating haptic actuators and fabrics, contributing to advancements in wearable technology.

7.2 Haptic Actuators and Fabric Integration in Wearable Toolkits

Our workshop findings showed that HaptiFab expanded the designer's diverse design space by integrating varied and functional haptic devices into fabric-based wearable designs. Participants noted that inherently static fabrics could provide richer emotional experiences when combined with haptic sensations, enhancing immersion. This underscores that haptic sensations and fabric integration play a significant role because haptic sensations could leverage the fabric's core advantages, such as flexibility and tactile comfort, to new levels in wearable design.

To implement this, the interaction and sensation capabilities of haptic actuators during prototyping could be prioritized, with fabric serving as a carrier to ensure wearability. During hands-on experiences with HaptiFab, participants found that HaptiFab reduced the technical and design complexities of integrating haptic actuators with fabric, which in turn helped participants explore and expand their design space more effectively. For example, fashion designers without engineering backgrounds were able to create desired interactive experiences across disciplines easily. We believed this integration amplified designers' creativity, enabling new design possibilities by blending rapid learning with existing skill sets. These findings highlight HaptiFab's potential to foster innovative designs while supporting a more inclusive interdisciplinary design process.

7.3 Limitations and Future Design Opportunities

Haptic Sensation Integration for Wearable Design. Through the successful completion of prototypes by all seven interdisciplinary groups, this workshop demonstrated the effectiveness of collaborative efforts in accelerating processes and addressing design complexity [88]. By exploring participants' considerations, challenges, and design spaces in integrating different haptic sensations and fabrics for wearable design, this work highlights the critical role of aligning haptic sensation choices with specific user goals. The findings reveal that different user needs—ranging from comfort and functionality to emotional engagement—demand tailored haptic solutions, making the exploration of goal-driven haptic integration a key avenue for future research. These insights offer valuable guidance for HCI researchers and designers in the fields of wearable technology to address diverse and evolving user goals.

Software Simulation Design Tool for Enhancing Interdisciplinary Design. Our findings show that all seven groups encountered minimal barriers when selecting fabrics, likely due to their familiarity with daily use. However, designers selecting haptic actuators faced challenges, requiring multiple iterations to identify suitable options. The inherent physical properties of certain actuators (P3, P4), such as the heat generation of SMA, are influenced by participants' preferences. Moreover, due to the 5-day workshop's time constraints and cognitive load, there were limitations in fully exploring the haptic sensations and fabric properties [108]. To address these challenges, developing a software design tool, to support interdisciplinary collaboration would be beneficial [10]. Such a tool could digitize the design manual, simulating the integration of haptic actuator parameters with fabric deformation and enhancing the design process. It also can integrate research on haptic effects and user perception, such as mapping user expectations to haptic parameters [109] and generating customized layouts [110], with software that recommends haptic parameters based on design scenarios.

More Portability and Adaptability Future. Additionally, while each group successfully achieved its desired outcomes and functionalities, we observed that some prototypes, such as those from Group G2, were larger than expected. P7 mentioned that this limitation was due to the insufficient PWM output channels of HaptiFab's electronic modules needed to drive the vibration motor matrix. To address these kinds of issues, future work should focus on customizing driver modules that improve the portability and offer greater adaptability of HaptiFab to accommodate complex vibration control requirements [22, 46]. Furthermore, as a wearable device, it is crucial to consider the modularity and detachability of haptic actuators, as well as durability, dirt resistance, and washability (P18). These improvements will help future toolkits meet the practical demands of long-term and versatile applications.

Expanding Beyond Wearable. Furthermore, our participants also envisioned broader applications beyond wearables, such as tangible toys (P6), therapeutic devices (P14, P25, P7), and sleep aids (P8). Our preliminary findings suggest that integrating haptic actuators and fabric within a single toolkit can significantly benefit wearable technology design. However, a gap remains in systematically understanding how specific haptic sensations contribute to the design workflow. Future toolkits should incorporate multi-sensory features to help users effectively visualize haptic simulations, as suggested in previous studies [30, 110].

8 CONCLUSION

In this paper, we present HaptiFab, a wearable toolkit designed to support the integration of haptic actuators with fabric, assisting designers and engineers in balancing technical and design aspects during prototype creation. Through a five-day workshop study, our toolkit demonstrated its adaptability in supporting diverse design purposes, ranging from functional wearables to emotional and educational applications. We reported participants' perceptions and considerations regarding using HaptiFab for wearable technology in detail and outlined directions for future design space. Our findings also indicated that HaptiFab lowers barriers to entry for designers and engineers, fostering collaboration for Interdisciplinary Design. We finally discussed the advantages of fabric and haptic integration to empower interdisciplinary groups to create innovative wearable solutions. In conclusion, we explored the potential of integrating different sensations with fabric in wearable toolkits, enabling the creation of practical, inclusive, and emotionally resonant designs tailored to varied user scenarios.

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A Appendix A: Design Manual

This section provides an overview of the Design Manual, which guides users in integrating haptic actuators and fabrics. The manual outlines key steps and design considerations for the effective use of HaptiFab.

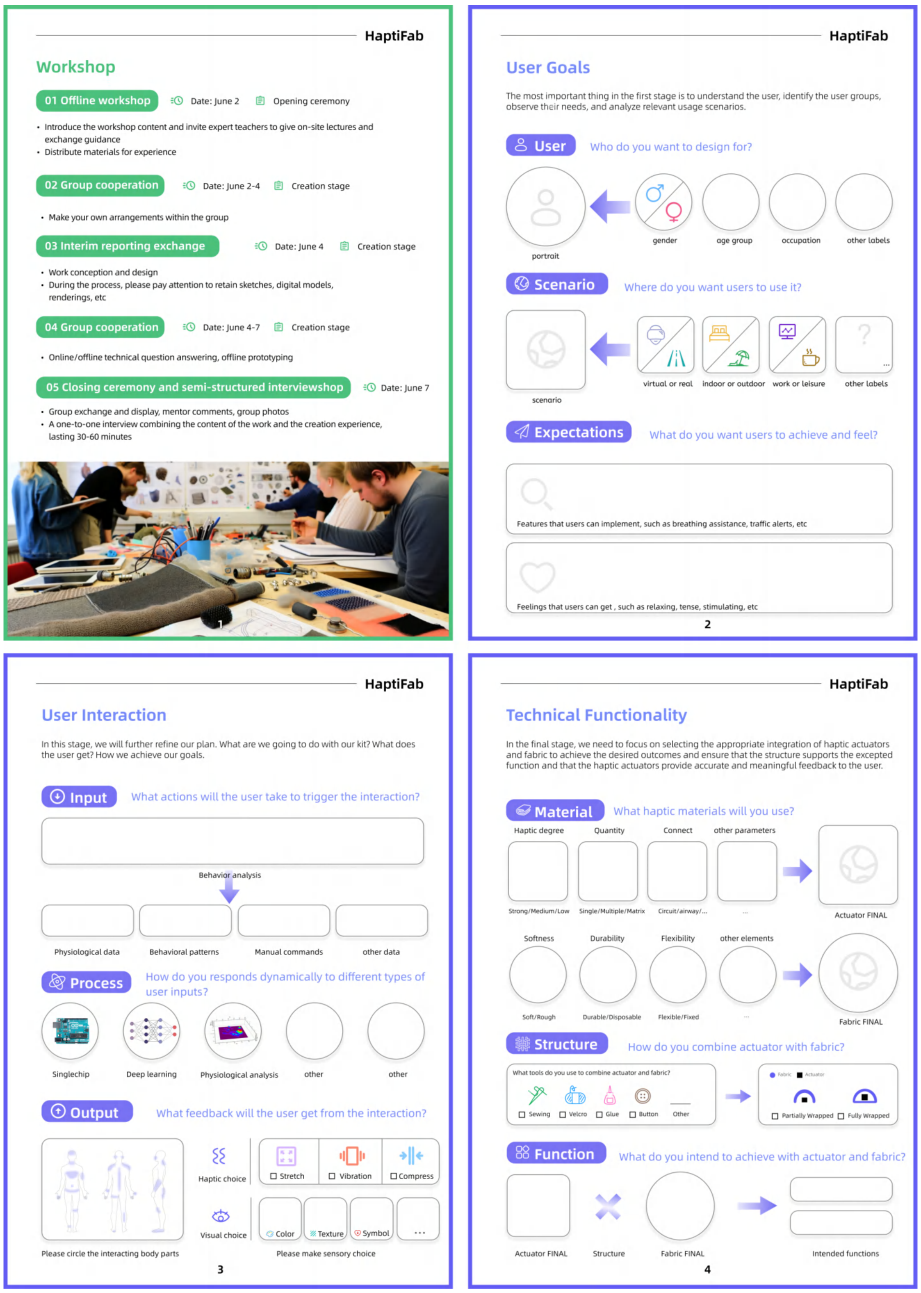
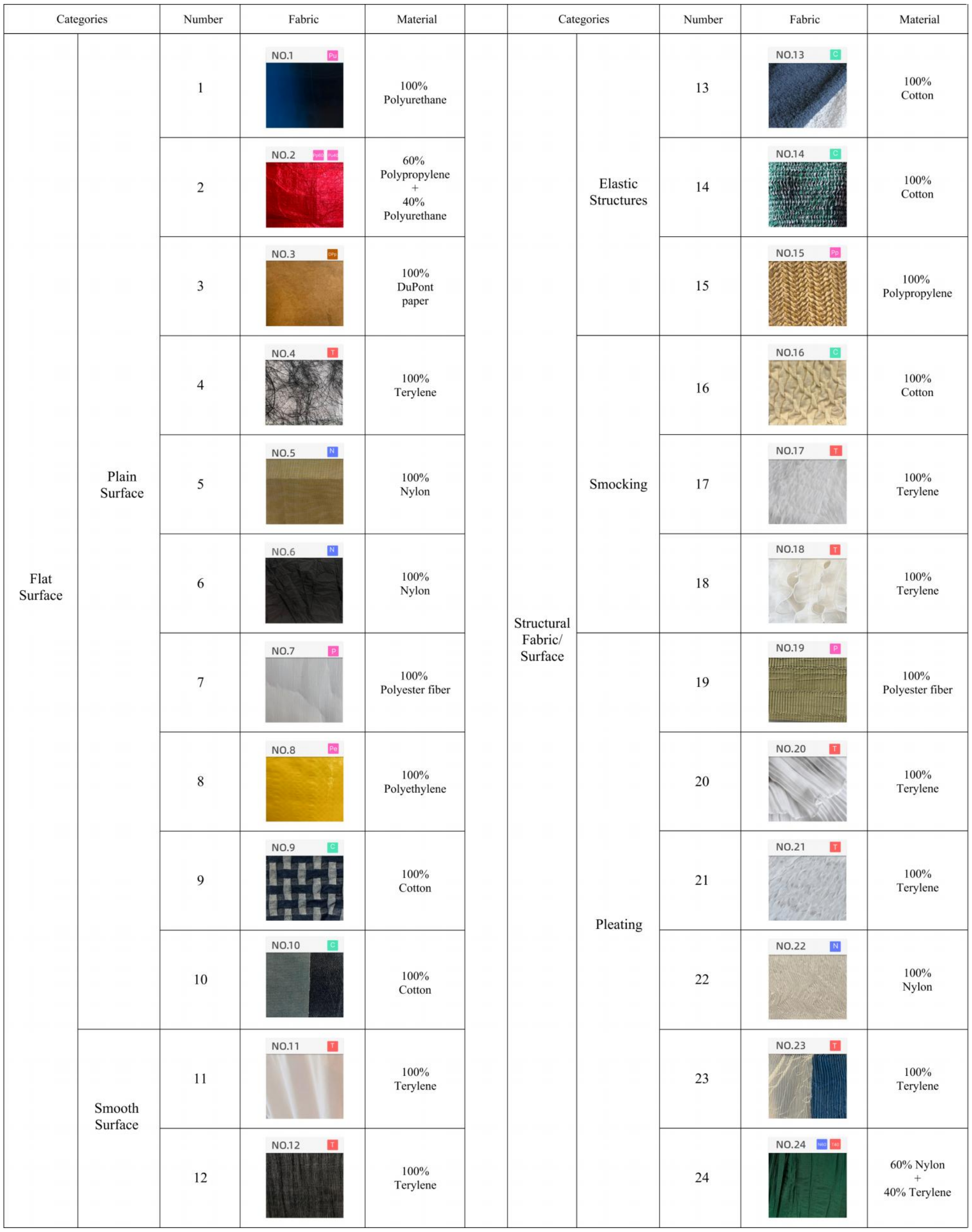


Fig. A.1. Design Manual Overview. p1) Workshop Arrangement, p2-p4) Design Guide.

Fig. A.2. Design Manual Overview, p5-p6) Actuators Display in toolkit, p7-p8) Fabrics Display in toolkit

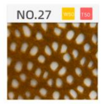
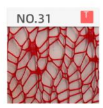
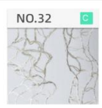
B Appendix B: Fabric Classification

This section categorizes fabrics based on their properties and construction techniques, while also explaining the materials used in different fabrics.



Categories		Number	Fabric	Material	Categories		Number	Fabric	Material
Flat Surface	Plain Surface	1	NO.1	100% Polyurethane	Structural Fabric/ Surface	Elastic Structures	13	NO.13	100% Cotton
		2	NO.2	60% Polypropylene + 40% Polyurethane			14	NO.14	100% Cotton
		3	NO.3	100% DuPont paper			15	NO.15	100% Polypropylene
		4	NO.4	100% Terylene		Smocking	16	NO.16	100% Cotton
		5	NO.5	100% Nylon			17	NO.17	100% Terylene
		6	NO.6	100% Nylon			18	NO.18	100% Terylene
		7	NO.7	100% Polyester fiber		Pleating	19	NO.19	100% Polyester fiber
		8	NO.8	100% Polyethylene			20	NO.20	100% Terylene
		9	NO.9	100% Cotton			21	NO.21	100% Terylene
		10	NO.10	100% Cotton			22	NO.22	100% Nylon
	Smooth Surface	11	NO.11	100% Terylene			23	NO.23	100% Terylene
		12	NO.12	100% Terylene			24	NO.24	60% Nylon + 40% Terylene

Fig. B.1. Fabric Categories and Materials Explanation - 1

Categories		Number	Fabric	Material
Structural Fabric/ Surface	Cutwork	25		100% Terylene
		26		100% Cotton
		27		50% Wool + 50% Terylene
		28		57% Rayo + 43% Terylene
		29		100% Cotton
		30		65% Acrylic + 35% Terylene
		31		100% Terylene
		32		100% Cotton
	Mesh	33		100% Terylene
		34		100% Terylene
		35		100% Terylene
		36		100% Terylene

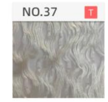
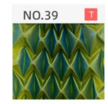
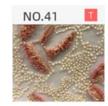
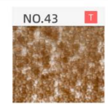
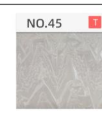
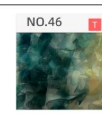
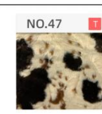
Categories		Number	Fabric	Material
Structural Fabric/ Surface	Ripple Structures	37		100% Terylene
		38		100% Terylene
	Origami Structures	39		100% Terylene
		40		100% Polyurethane
Decoration Surface	Embroidery	41		100% Terylene
		42		100% Terylene
	3D Surface Embellish -ments	43		100% Terylene (excluding embellishment)
		44		100% Terylene (excluding embellishment)
		45		100% Terylene
		46		100% Terylene
	Pile	47		100% Terylene
		48		100% Terylene

Fig. B.2. Fabric Categories and Materials Explanation - 2

C Appendix C: Practical Applications

This section highlights practical applications developed by our seven interdisciplinary groups during workshop prototyping, following the design manual process, and utilizing HaptiFab.

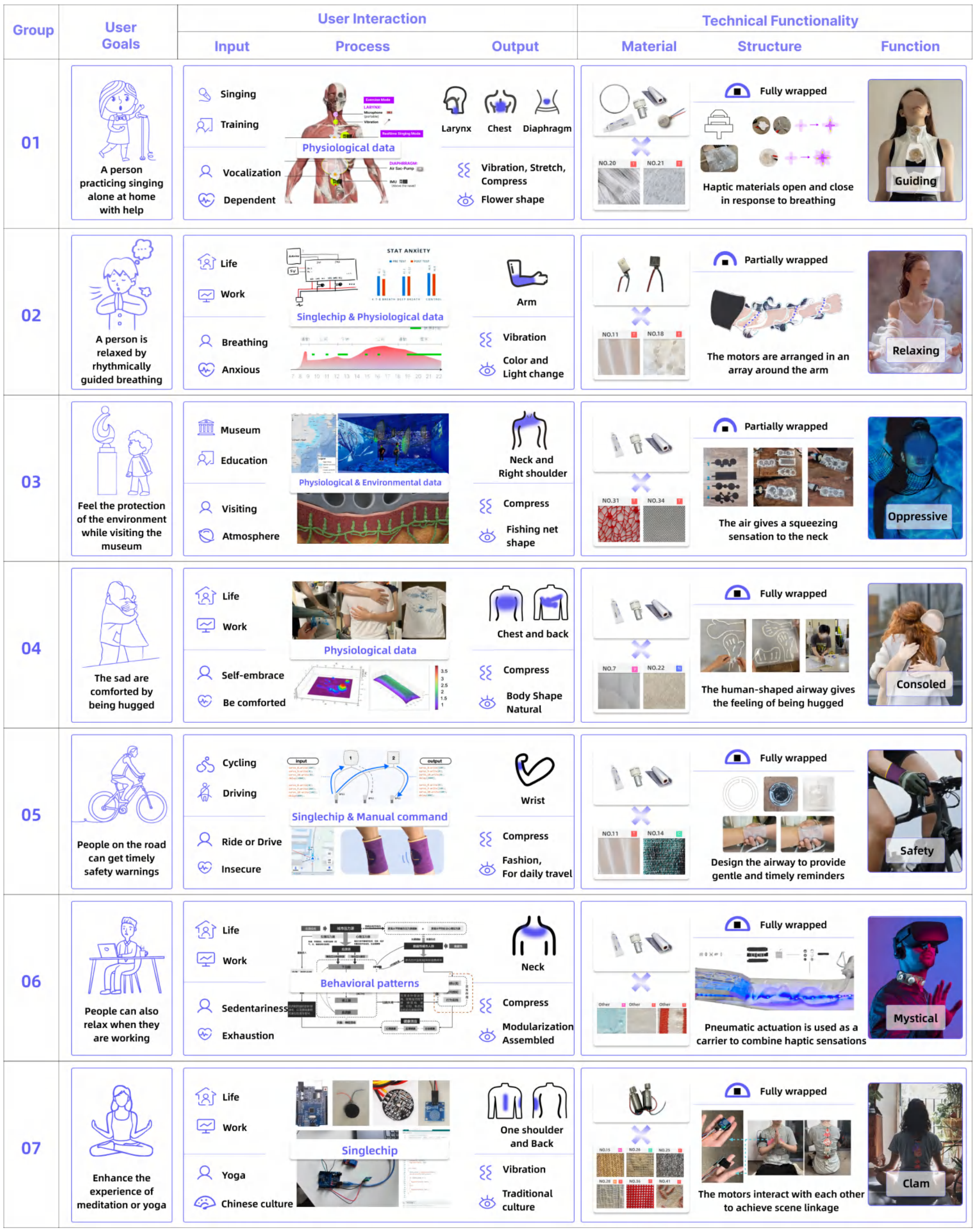


Fig. C.1. Mapping with Workshop Case to Evaluating Workflow

D Appendix D: Question List

This section summarizes the semi-structured interviews conducted to evaluate HaptiFab. The interviews cover topics such as interdisciplinary design, haptic integration, and user experience.

Table D.1. Interview Topics and Sample Questions

Interview Topics	**Interview Guide**
Demographic	1. How old are you? Studying or working? What's the grade? What is your major background or research direction? 2. Do you have any previous work or program experience?
Toolkit Usage and Effectiveness	1. How did you utilize the HaptiFab in your program? What role did it play in the interdisciplinary design process? 2. In your view, how effective was the HaptiFab in lowering the barriers to prototyping? Did it open up new design spaces? 3. What could be improved in the HaptiFab to better support users?
Integration of Haptic Actuator and Fabric	1. Why did you choose the specific fabric used to enclose the haptic Actuator? What were its advantages in terms of supporting your design goals? 2. What motivated the choice of specific haptic mechanisms (Stretch-SMA, Compress-pneumatic actuation, Vibration-motors)? How did they align with your design objectives? 3. How do you assess the performance of these integrations of haptic actuator and fabric across different contexts? Were there any noticeable deviations or preferences based on user scenarios?

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