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.

Haptic actuators, as essential components for human sensory interaction, have been widely adopted and integrated into portable wearable devices. As carriers of wearable technology, fabric delivers haptic feedback that makes direct contact with the skin. In this context, we propose HaptiFab, a wearable toolkit that supports the integration of haptic actuators and fabric for interdisciplinary design, offering rich sensations and a broad design space across various wearable applications. Through a 5-day workshop with 30 participants, we demonstrated that HaptiFab can reduce technical and design complexity while enabling the prototyping of diverse haptic sensations. Based on the workshop findings, We developed a systematic workflow for integrating haptic actuators with fabric to help designers and engineers collaborate effectively within interdisciplinary teams, enabling innovative applications in wearable technology.

CCS Concepts: • **Human-centered computing → User interface toolkits**.

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

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1 INTRODUCTION

Haptics is an important form of sensation that can assist wearable technologies in realizing specific functions, conveying affective information, and improving psychological experiences because it is widely distributed across the surface of human skin [1, 2]. Recently, more and more researchers are transferring physically-grounded haptic interfaces [3] to haptic actuators [4], which allows users to utilize the wearable technology at more desired points of stimulus actuator on the body [5], offering better possibility, portability and versatility [6]. As an essential material could also provide unique haptic sensation, fabric plays an essential role in wearable technologies to energy harvesting, motion and attitude sensing and comfort evaluation [6–9]. By leveraging the wearability of fabric 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] and providing immersive experiences in virtual reality [12].

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 not only because haptic actuators (such as pneumatic silicone [13], vibration motors [4, 14], and shape memory alloy (SMA) [12, 15, 16]) and fabrics (such as Soft-Harsh [17, 18] and Smooth-Rough [17, 18]) are varied, but also because different types of haptic sensations (such as compression [19], friction [20], stretch [21], and vibration [22, 23]) contribute to different sensory experiences. Thus, selecting the most appropriate components in wearable technologies becomes a significant challenge due to the numerous options available.

In addition, wearable technology usually requires people master different domain expertise and interdisciplinary skills, such as interaction design [24], fashion design [25], and programming [26]. Designing process is deeply intertwined with human perception [27], usually rely on a user-centered approach [28] that combines research through design [28] with technical implementation. Thus, individual may find it challenging to seamlessly integrate haptic sensation with fabric design and technical engineering, as this requires not only an understanding of the user's sensory experience but also the ability to promote technically feasible [29]. It is uncommon to find a programming designer with the strong capability to manage interdisciplinary workflows effectively. Given these difficulties, previous researchers developed wearable toolkits to facilitate this complex design process due to the advantages of simplify prototyping [30, 31], demystify abstract hardware and software concepts [32]. However, there are some existing issues, including limited customization options [33], complexity of integration [34], poor material compatibility [25]. These issues highlight the need for enhanced flexibility and ease of use in toolkits to better support interdisciplinary design workflows.

With this context in mind, we aim to answer the following questions by designing a wearable toolkit supports the integration of haptic actuator and fabric for interdisciplinary design:

- RQ1: How to involve multiple haptic sensations while reducing technical and design complexity?
- RQ2: What are the design space, and challenges when design wearable technology with fabric integration and haptic actuators?
- RQ3: How can a systematic workflow be designed for the integration of fabric and haptic actuators in wearable technology within an interdisciplinary context?

In this paper, we present HaptiFab, a toolkit with haptic actuators and fabric integration for interdisciplinary teams to design wearable technology. HaptiFab consists of three main components: a) Haptic Generation Kit, b) Fabric kit, and c) Design Manual to allows user to do DIY design prototypes without fully understanding the background of professional wearable technology. We conducted a five days workshop with 30 participants to forming seven interdisciplinary team to use HaptiFab for wearable technology design. We used the mixed research method, interview, observations, and questionnaire to evaluate HaptiFab by collecting participants' experiences and perspectives on HaptiFab usage. Our findings first report the design space and selection practices used by participants when designing wearable prototypes. Following findings we also proposed a systematic workflow that summarizes the prototyping process from a design perspective to provide valuable references and implications for interdisciplinary teams prototyping wearable toolkits.

In conclusion, our paper shows three main contributions: (1) We provided a toolkit using haptic actuators and fabric integration for wearable technology design. (2) We suggested selections, considerations, and challenges of how interdisciplinary teams practice and perceive the process of HaptiFab usage. (3) We proposed a comprehensive systematic workflow to support future interdisciplinary design using HaptiFab.

2 RELATED WORKS

2.1 Multiple Sensations of Haptic Actuator and Fabric

2.1.1 Haptic Actuator Sensations. In the field of wearable technology, haptic sensations triggered by external stimuli include vibration [22, 29], compression [17, 33, 35], stretch [16, 21, 36–38], contractile [39], bending [40], expanding [41], and pinching [41]. 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 [42], emotional communication [43], and entertainment game [34]. The three most commonly used actuation methods are compression, stretch, and vibration.

Compression. The sensations of compression is commonly achieved through pneumatic actuators [13, 17, 33, 35]. To provide a more fitting and safe application on the body, customized pneumatic silicone are very effective as compression devices [8, 44]. He et al. [8] utilize custom-molded pneumatic silicone to provide a range of haptic cues on the arm. Pohl et al. [44] explore various haptic sensation types produced by pneumatic compression, including subtle, intimate, and intense sensations.

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) are ideal for producing such haptic sensations by applying shear forces to stimulate the skin's deformation detection [45]. SMA is lightweight and compact, allowing for seamless integration without altering the overall shape, such as in haptic pin arrays [38, 46, 47] 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 [40, 48] and smart fabrics that support astronauts' cardiovascular systems [49, 50].

Vibration. Vibration actuators provide immediate yet sustained haptic feedback [29, 44]. Compact and low-power, vibration motors have been widely researched and applied in wearable technology, offering specific or symbolic haptic sensations [6, 17, 51], making them particularly suitable for use as drivers in wearable devices, such as emotion-based social media [22, 23, 42], garments for rehabilitation training monitoring [52], and devices that enhance VR experiences [53].

2.1.2 Fabric Sensations and Applications. Fabrics have been extensively applied in various domains, including artistic expression [54, 55], medical and therapeutic applications [56], assistive devices [57, 58], electronic clothing [59–63], input sensing [64, 65], robotic applications [66], and interactive products [67]. Jiao et al. evaluated various fabrics (such as cotton, nylon, and polyester wool blends) [68] and identified different sensations such as smooth-rough, soft-harsh, and hairy-stiff [69, 70]. Bhömer et al. explored anisotropic fabric structures through various prototyping methods, demonstrating their potential to enhance the skin-friendliness and comfort of wearable devices [25]. As carriers for wearable technology, fabrics can act both as active deformable materials [18, 71, 72] and as passive responsive materials [73]. Paradiso et al. integrated woven piezoresistive sensors into garments to explore haptic sensation brought about by deformation [74]. Granberry et al. used SMA to design fabric interfaces that can create various shapes suitable for user contraction [75] and compression deformation [76]. Different mechanical or structural mechanisms of fabrics [77, 78] can produce a variety of sensations, enriching user experience.

Hence, it is crucial in the field of wearable technology to effectively integrate the multiple haptic sensations generated by both haptic actuators and fabrics to meet user needs in various scenarios.

2.2 Haptic Prototyping Toolkits

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, 31, 79, 80]. These toolkits address challenges in design, fabrication, sensing, and actuation by introducing innovative materials and workflow design [81], creating functional physical widgets and control components [82], or developing integrated hardware and firmware environments [79], thereby lowering the barrier to entry and supporting the design of multiple haptic sensations for various body parts [31]. For instance, Compressables-based haptic interactions on various body parts support open-ended design [32] Beyond specific use cases, toolkits of Soma design enhance body awareness, foster aesthetic appreciation, and broaden the design space for intimate wearable technologies [83].

However, current wearable toolkits have yet to adapt to the diverse needs, as most are tailored to a single or limited range of contexts. Drawing on insights from the existing literature, our objective is to develop a wearable toolkit that supports the integration of universal haptic actuators and basic fabrics, enabling designers and engineers to create low-cost, DIY, rapid prototypes that can be adapted to various everyday scenarios without having to master multidisciplinary complex expertise.

2.3 Adapting Theoretical Design Models for wearable Technology

Interdisciplinary teams offer significant advantages, the most important being their ability to accelerate processes and address complexity [84]. Furthermore, interdisciplinary collaboration helps teams set shared goals, fostering a unified knowledge system [84]. As an interdisciplinary field, HCI needs to integrate design thinking and technical principles [85], emphasizing both the design process and user experience, while also focusing on technical feasibility and interaction principles.

For the design process, models like the Double Diamond [86], Knowledge Opportunities [87], and FBS (Function-Behavior-Structure) [88] all inspired our research. The FBS model, in particular, breaks down design into function, behavior, and structure, helping designers and engineers in defining a system's purpose and supporting actions. For example, Zhao et al. used the FBS model to develop an ergonomic stroke rehabilitation device [89]. Similarly, Hasso Plattner's five design thinking stages—empathizing, defining, ideating, prototyping, and testing—offer a structured approach to problem-solving [90]. On the user experience side, Norman's Emotional Design and Inclusive Design emphasize creating products that meet both functional and emotional needs, while ensuring inclusivity [91].

However, bridging design thinking with technical principles in an interdisciplinary context remains a challenge [85]. Models like Zimmerman et al.'s three types of knowledge—how, true, and real—serve as a framework for generating design ideas grounded in practical insights [28]. The Perception-Action Loop Model highlights real-time sensation between user perception and action, ensuring systems adapt naturally to user input [92], while the Cognitive Load

Theory emphasizes managing information complexity to avoid overwhelming users, thus enhancing usability [93]. In the integration of haptic actuator and fabric, it is crucial to consider both design thinking and technical principles [31]. This includes selecting appropriate haptic actuators [31] and fabrics [69]and physical properties of the fabric to ensure functionality while delivering a meaningful haptic experience in an interdisciplinary context. These integrated approaches can help designers and engineers balance creativity and technical rigor [80], ultimately resulting in innovative yet practical wearable solutions.

3 HAPTIFAB: TOOLKIT IMPLEMENTATION

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 [32, 79] and design-centered approaches [31]. 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 design principle and features introduction about HaptiFab.

3.1 Design Principles

Based on our Section 2, we summarized a series of limitations of current wearable toolkits and the challenges of integrating haptic actuators and fabrics, including 1) Limited Customization Options [33], 2) Complexity of Integration [34], 3) Poor Material Compatibility [25]. Thus, we aimed to meet the following three design principles:

- Wearability: Since different parts of the body have varying sensitivity thresholds, the haptic sensations experienced can differ across regions. As a wearable device, HaptiFab should support designs for all body parts, with haptic materials that easily adapt to the shape and size of the user's body, enhancing both comfort and flexibility [80].
- Adaptability: To ensure HaptiFab can meet the needs of different scenarios and accommodate specific user expectation, we offer a variety of haptic modules in different sizes and configurations. These combinations allow for diverse sensory experiences, catering to individual preferences.
- Interdisciplinary: To reduce technical barriers for non-programmers, we have integrated waveform generators and adapter power into the haptic generation kit, which require no programming skills. Additionally, we provide 42 different materials and textiles, ensuring the modules are versatile enough to meet the diverse needs of designers and engineers across multiple fields.

3.2 Toolkits Features and Components

3.2.1 *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.

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

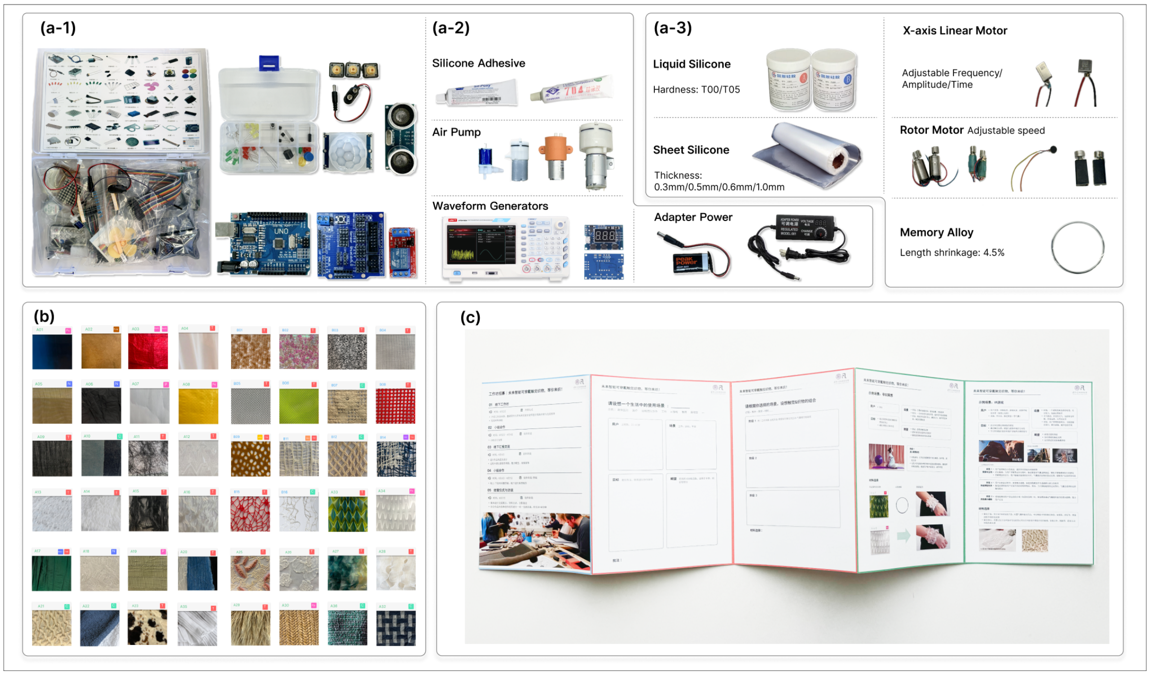

Fig. 2. HaptiFab overview. a) Haptic Generation Kit, a-1: electronic modules, a-2: driver and adhesion modules, a-3: output components, b) Fabric kit, c) Design Manual.

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.

Driver and Adhesion Modules. Our toolkit also provides Driver and Adhesion Modules, which assist designers and engineers in bonding and actuating haptic actuators. For liquid silicone, the actuator typically needs to set for about 45 minutes, while sheet silicone requires bonding with a specialized silicone adhesive, available in clear and milky white. All pneumatic silicone actuators must be inflated using an air pump. We offer 12V, 24V, and 36V air pumps, each with multiple electromagnetic valves to control airflow. SMA can stretch when electrically powered.

Haptic Output Actuator. Based on literature reviews in the ACM Library, we identified three commonly experienced haptic sensations: Compression [8, 44], Vibration [22, 23, 42], and Stretching [37, 45, 51]. As illustrated in Fig.3, these sensations are commonly associated with specific haptic actuators. We then selected three haptic actuators: Pneumatic Silicone, Vibration Motor, and Shape Memory Alloy based on their ability to produce these desired sensations effectively. These actuators were chosen for their low cost and DIY-friendly implementation, making them suitable for our study. All output components 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, enabling designers to adjust frequency, amplitude, and duration without requiring programming skills. By utilizing arbitrary waveform generators, designers can fine-tune these parameters with ease. In addition, Shape Memory Alloy (SMA) are incorporated to simplify the power requirements for non-technical users through adapter power, ensuring ease of use. Pneumatic silicons elements require inflation using an air pump, further expanding the range of haptic experiences while maintaining simplicity in operation.

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

Fig. 3. Physical Sensation Corresponding to Different Haptic Actuators

Pneumatic silicone include liquid silicone and sheet silicone. There are different parameters that designers and engineers can choose. The hardness of liquid silicone include T00 and T05, the thickness of silicone sheet include 0.3mm/0.5mm/0.6mm/1.0mm. The greater the hardness or thickness, the greater the air needed to drive the silicone to deform.

Vibration motor include X-axis Linear Motor, which can be adjusted Adjustable Frequency/Amplitude/Duration, the models include AAC Company's 1016 motor. For the convenience of more designers who don't know about the motor's parameters, we also chose a different structure of rotor motor, which can be adjusted Adjustable speed. To make it easier for designers who don't know the parameters of the motor, we have also chosen a different style of rotor motor, which is only adjustable in speed, and has less variations than the X-axis Linear Motor, but is easier to use.

Shape Memory Alloy There are two common ways to drive SMA in the market nowadays, which are electrical deformation and heating deformation. Considering the limitations of wearable devices, we chose NiTi Memory alloy with energized deformation, and the deformation mechanical test is 4.5 per cent of length shrinkage after energization.

3.2.2 Fabric Kit. For fabric that comes into direct contact with the skin, haptic properties are important in relation to clothing comfort [70]. Pressure and friction forces are critical parameters of sensory stimuli and haptic feel [94]. We offer 42 different fabrics, including polyester, wool, and cotton, to meet a wide range of usage scenarios [11], as illustrated in Fig.2 b. 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]. Customization using knitting machines and looms is encouraged. The fabric selection takes into account the different haptic sensations associated with various weaving methods and material choices, such as the *rough* texture of irregularities or protuberances, and the *prickle* feel of many very gentle pin picks [70], which allows the user to make better categorization and differentiation.

3.2.3 *Design Manual.*

The design manual, as illustrated in Fig.2 c, guides users through the prototyping process from a design discipline perspective, drawing on the 5 Phases of Design Thinking [96], the FBS Model [88], and Research Through Design [28]. This manual aids designers and engineers in constructing the 3 phases: User Goals (user-scenario-expectation), mapping User Interaction (Input-Process-Output), and defining Technical Functionality (material-structure-function). By following the step-by-step guide, designers and engineers can incorporate unfamiliar materials into their creations more seamlessly and effectively.

User Goals (User-Scenario-Expectations). Before starting the design, it is crucial to identify the user groups, observe their needs, and analyze relevant usage scenarios. This phase focuses on understanding the users' pain points and translating them into clear design goals. Tools such as storyboards, sticky notes, and paper templates can assist in visualizing user journeys and scenarios [29, 37, 92]. Conducting user interviews and field observations can further help uncover implicit needs and expectations. 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 system, including the types of inputs they provide, the processes that occur in response to those inputs, and the eventual outputs or feedback they receive. During this phase, designers and engineers should define how the system responds dynamically to different types of user inputs, such as physiological data [5], behavioral patterns [44] or manual commands [67]. This step involves mapping out the interaction flow, ensuring that the user's input leads to an intuitive and adaptive process within the system [34]. By thoroughly analyzing the interaction process, designers and engineers can ensure that the output effectively meets the user's needs, creating a seamless and engaging experience.

Technical Functionality (Material-Structure-Function). When defining technical functionality, designers and engineers need to focus on the selection of appropriate integration of haptic actuators and farbic to achieve the desired outcomes. This phase requires careful consideration of how the chosen materials interact with each other and how their properties (e.g., flexibility, durability, texture) affect the overall design. Additionally, designers and engineers must ensure that the structure supports the intended function and that the haptic actuators provide accurate and meaningful feedback to the user. Adjusting material parameters to match the functional requirements of different haptic feedback types is critical in achieving a coherent and satisfying user experience. This phase ties the entire design together by ensuring that the physical and technical aspects [69] align with user expectations and interaction goals.

4 WORKSHOP

To evaluate HaptiFab, we conducted a workshop with 30 participants, divided into seven interdisciplinary teams. The workshop explored how designers and engineers used HaptiFab for interdisciplinary collaboration. We also observed the design process and prototypes developed by each team, gathering valuable insights and feedback on our toolkit. This helped us explore potential design spaces and workflows across different use cases.

4.1 Process

4.1.1 *Participants Recruitment.*

We posted our recruitment message on social platforms for ten days and received 182 applications. Participants were selected based on the following criteria: (1) Availability to attend the entire onsite workshop in Beijing, (2) Submission of a portfolio demonstrating a basic understanding of haptic or fabrics, and (3) Expertise in a relevant research field, such as fashion design, interaction design, or engineering, with the capability to produce comprehensive interaction design work.

Ultimately, we recruited 30 participants (7 males, 23 females), aged 19 to 37 (M = 24.07, SD = 3.87) for this workshop, as shown in Table.1. Most of them were undergraduate and graduate students from a north Chinese city, with some international students. Participants will form interdisciplinary teams during the 5-day workshop and use HaptiFab to conduct research, design, and develop interactive prototypes incorporating haptic fabrics. We also selected 11 workshop assistants from our lab, all with relevant research experience and backgrounds. Five days before the official start of the workshop, we provided pre-training to ensure they were familiar with the workshop's production techniques and research objectives. During the workshop, these assistants joined various groups to offer technical support.

4.1.2 Opening Ceremony. Firstly, our mentor introduced the research content and directions currently being pursued in our lab regarding wearable technology. The workshop leader then detailed the specific goals and research content of this workshop, providing examples of possible usage scenarios to guide participants' thinking. We held ice-breaking activities to help everyone form teams freely, resulting in seven groups of 3-4 people each, with 1-2 moderators assigned to each group. The leader then introduced the technologies to be used in the workshop, such as pneumatic silicone prototype creation, vibration motor usage, and memory alloy utilization.

4.1.3 Prototype Making. After the opening ceremony, each group began their design work. During the five day workshop, moderators regularly checked the progress and provided technical guidance to the groups. On the third day of the workshop, we held an offline mid-term exchange meeting where each group presented their design prototypes, mainly focusing on application scenarios and the technologies used. Our mentor provided sensation, asked questions, and offered answers. In the following three days, groups refined their designs based on this sensation and conducted several tests to optimize their physical prototypes performance, ensuring optimal presentation.

4.1.4 Final Presentation and Interviews. On the Five day of the workshop, we held a three-hour closing ceremony to facilitate mutual learning among participants and to receive sensation from mentors. As shown in Table.2, each group presented their projects, detailing design rationale, technical specifics, and usage methodologies. The mentors then provided critiques, asked questions, and offered answers.

The final stages of the workshop involved collecting sensation from participants through a User Experience Questionnaire (UEQ) [97] for HaptiFab and semi-structured interviews. The questionnaire featured 26 items across six dimensions—attractiveness, efficiency, perspicuity, dependability, stimulation, and novelty, utilizing a 7-point Likert scale to assess participants' actual usage experiences of HaptiFab, focusing on its pragmatic and hedonic qualities of haptic technologies and fabric materials. The semi-structured interviews, conducted in each group for 60 minutes and recorded in audio format.

4.2 Data Collection and Data Analysis

We collected videos and images during the workshop, as well as prototypes from the seven teams. To assess user perceptions of HaptiFab, we conducted a quantitative analysis of the UEQ results based on Appendix.B. Additionally, we gathered and transcribed audio recordings from the interviews, the interview guidline are based on Appendix.A. For qualitative analysis, we performed a thematic analysis [98] of the interview transcripts. This process involved several rounds of discussion to identify and summarize key themes based on participants' evaluations of the toolkit and the

Table 1. Participant 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	Fashion and Engineering
G3	P9	F	25	Postgraduate	Interaction Design
	P10	M	23	Postgraduate	Interaction Design
	P11	F	22	Undergraduate	Fashion Accessories Design
	P12	F	37	Postgraduate	Learning Design
G4	P13	M	26	Postgraduate	Wearable Design
	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	Interactive Media Design
	P19	F	29	Postgraduate	Digital Intelligence and Fashion Art
	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
	P24	F	20	Undergraduate	Interaction Design
	P25	F	22	Undergraduate	Interaction Design
G7	P26	M	23	Postgraduate	Art & Design
	P27	F	28	Postgraduate	Art & Technology Design
	P28	F	21	Undergraduate	Fashion Design and Engineering
	P29	F	26	Postgraduate	Textile Design
	P30	F	19	Undergraduate	Digital Media Arts

workshop. Two researchers initially reviewed the field data (prototypes, images, manuals). Any disagreements during coding were resolved through joint discussions and consultation with a third expert (the third author) until a consensus was reached.

5 FINDINGS

In this section, we present the findings from the semi-structured interviews conducted with participants and observations of the prototypes created during the workshop, refer to Figure 4 and Table 2 for details. We also discuss the design space and considerations for HaptiFab, including various dimensions of the design process, material choices, and interaction modalities identified by participants.

Table 2. Prototypes Description

	Group	Thematic	Haptic Actuator	Description
Functional Wearables	G1	HarmonicWeave (Fig.4 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.4 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.4 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.4 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.4 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.4 g)	Vibration motors	The design uses vibrating motors to provide 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.4 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 Examining Participants' Exploration of Haptic Actuators Integration

During the workshop, we observed that participants generally recognized the significant role haptic actuators play in prototype development. More than half of the participants (N=16: P1, P4, P6, P7, P9, P10, P11, P16, P17, P18, P19, P21, P23, P26, P28, P29) highlighted this in their interviews. Their primary consideration when designing prototypes based on the design manual was whether the haptic actuators aligned with the scenario and user expectations. Therefore, this section focuses on reporting participants' selection of various haptic sensations and their corresponding feedback.

5.1.1 Body Part Selection. After participants established their *user goals*, they considered which body parts of the wearable would be most suitable. This selection was influenced by various factors, including different functionalities, user interaction needs [2], and sensitivity thresholds, which are further influenced by factors such as age [99] and body posture [100]. Our participants shared that they would consider both the physiological and practical aspects when selecting body parts for haptic sensation.

Fig. 4. 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.

Sensitivity and Acupoint Targeting. For instance, in G3's educational exhibit, designed to evoke a feeling of suffocation and entrapment, the neck was selected as a key body part due to its sensitivity and symbolic association with breath control. Pneumatic silicone and fabric were used around the neck to simulate the sensation of being trapped in a fishing net, and the *"Fengchi* [1] *"* acupoint was specifically targeted. The inflation of the silicone material created a sore, tight feeling, intensifying the sensation of discomfort (P10). The choice of the acupoint allowed the designers and engineers to leverage established sensory pathways to produce a distinct and immersive user experience.

Body Thresholds and Haptic Precision. In G4's design, aimed at replicating the sensation of a hug, the variation in sensory thresholds across different body parts played a crucial role. Areas such as the back, which have a higher two-point discrimination threshold [101], require larger and more forceful pneumatic silicone compared to more sensitive areas like the hands or arms. Participants could perceive the overall shape and pressure of the hug, but not the finer details of hand movements. Finite element analysis was used to extract the pressure distribution of a real hug, which G4 applied to their prototype to replicate the experience with greater haptic realism, as illustrated in Fig. 5 d. Similarly, G6's prototype focused on the sensation of submersion in seawater. The neck's high sensitivity, as described in P22, was a key consideration. The design incorporated precise pneumatic sensation and various fabric textures to mimic the feeling of seawater moving against the neck, enhancing the user's immersive experience.

G5's design also took into account body thresholds, focusing specifically on the wrist, which has a lower threshold and is more sensitive to directional cues. As mentioned in P17, *"The wrist's low threshold makes it ideal for navigation, where clear directional signals like left or right are crucial."* This decision to use the wrist for haptic sensation supported the functional requirements of the design.

[1]FengChi 风池 refers to an acupoint located in the hollow area at the base of the skull, just below the hairline. Pressing on this point may cause a sensation of soreness or mild pain, and regular stimulation can help relieve headaches, relax neck muscles, and improve vision problems caused by fatigue.

Functional Considerations. The specific functions of the prototypes influenced which body parts were chosen for haptic sensation. For G1, the focus was on enhancing participants' control over their vocal output during singing. This was achieved through haptic sensation applied to the throat, diaphragm, and chest. As noted in P1, *"In traditional teaching, students feel the teacher's throat to observe the duration and intensity of vibrations."* G1 integrated this concept by placing vibration motors at the throat, enabling participants to feel the vibrations corresponding to vocal frequencies in real-time. This provided tangible sensation on pitch and voice modulation. Additionally, G1 incorporated a 15x20 cm air bladder at the diaphragm, which compressed in sync with the user's breathing. This feature helped participants maintain steady breath control, supporting sustained vocalization and better pitch stability (P1, P2). By addressing both the physiological and functional aspects of singing, G1's design enabled participants to improve their vocal performance through direct, body-specific sensation.

5.1.2 Haptic Actuator Selection.

Pneumatic Silicone. Pneumatic silicone is the most frequently used material in our study, largely due to its capacity to provide large-area force sensation and a soft contact surface that adheres comfortably to the skin (P15, P17, P18, P21). P15 highlighted that *"the large-area haptic sensation from pneumatic silicones can simulate the feeling of a hug or an embrace, providing participants with a sense of supportive sensation."* As illustrated in Fig. 5 a, P2 also emphasized that large-area pneumatic silicone components are particularly well-suited for close body contact. Additionally, the adaptability of pneumatic silicone, which allows for modifications in volume and shape, enhances its design flexibility and expands its range of applications [102]. its reliance on pneumatic mechanisms can also pose constraints in terms of design portability and precision.

Shape Memory Alloy (SMA). Regarding the use of shape memory alloy (SMA), participants believe that SMA can achieve multi-angle deformation through structural combinations. Participants like P3 noted SMA's strong embedding properties, making it suitable for use in wearable devices where space is limited. Despite this, participants(P24, P25), acknowledged the limitations of SMA, such as its insufficient deformation amplitude, long response time, and slow deformation speed. While SMA excels in providing structural adaptability in compact spaces, these drawbacks significantly limit its use in scenarios requiring immediate or large-scale haptic sensation (P4). Its integration into wearables may be more effective in situations where subtle changes are preferred over instantaneous responses, but further refinement is needed to overcome the technical challenges associated with its application.

Vibration Motor. Vibration motors were praised by participants like P26 for their precision and timely sensation, offering the direct and adjustable haptic sensations. Their small size and powerful vibrations make them suitable for integration into wearable designs, where discretion and responsiveness are crucial. However, as P17 observed that *"The small size of motors requires close proximity to the skin for effective sensation, which can limit their application in designs that involve larger or less direct contact surfaces."* P18 emphasized the challenge of vibration synthesis, explaining that *"Precise calculation of vibration synthesis is required for wearable applications. It's not just about using one vibration motor. Several motors may need to be combined to synthesize a haptic sensation, like vector synthesis to create a point of vibration."* This complexity was further illustrated in G2's design, where an array of motors was used to expand the range of skin deformation, as shown in Fig. 5 b. While vibration motors offer precision, their effectiveness is often dependent on thoughtful arrangement and synchronization, particularly in applications that demand comprehensive, multi-point sensation.

5.1.3 Parameter Selection. In discussing the integration of haptic actuators and fabrics, various combinations within and between them can yield distinct haptic effects. The design of air pathways and pressure application, along with different thicknesses, significantly influences these outcomes. For instance, P3 notes that sheet silicone with a thickness of 0.3 are prone to bursting, while P4 emphasizes the use of liquid silicone glue for bonding due to its robust adhesive properties. In terms of prototypes involving SMA (shape memory alloy), adjustments to the format and parameters of vibration motors have been critical. For example, G2 adjusted each motor's parameters and arranged them in an array to create a vibrating cycle, which necessitated examining the literature to determine the specific sensations elicited by different waveforms—sinusoidal waves, for instance, are known for their effectiveness in awakening sensations.

During the workshop, we discovered certain limitations in using single materials for haptic sensation in terms of richness and conformity. P17 pointed out that a single material could be deficient in providing complex haptic sensation, and P21 mentioned that using motors alone tends to produce monotonous and static effects. Therefore, many groups combined different haptic effects to create a more dynamic experience. Regarding material combinations, G1 integrated shape memory alloy with motors, while G6 combined pneumatic silicone with motors for enhanced haptic sensation. Additionally, the placement of haptic sensation played a crucial role; G1's haptic sensation involved the throat and abdomen, whereas G7 focused on linking the back and shoulders. This diverse approach to integrating haptic materials and fabrics underscores the potential to tailor haptic experiences to specific user needs and scenarios.

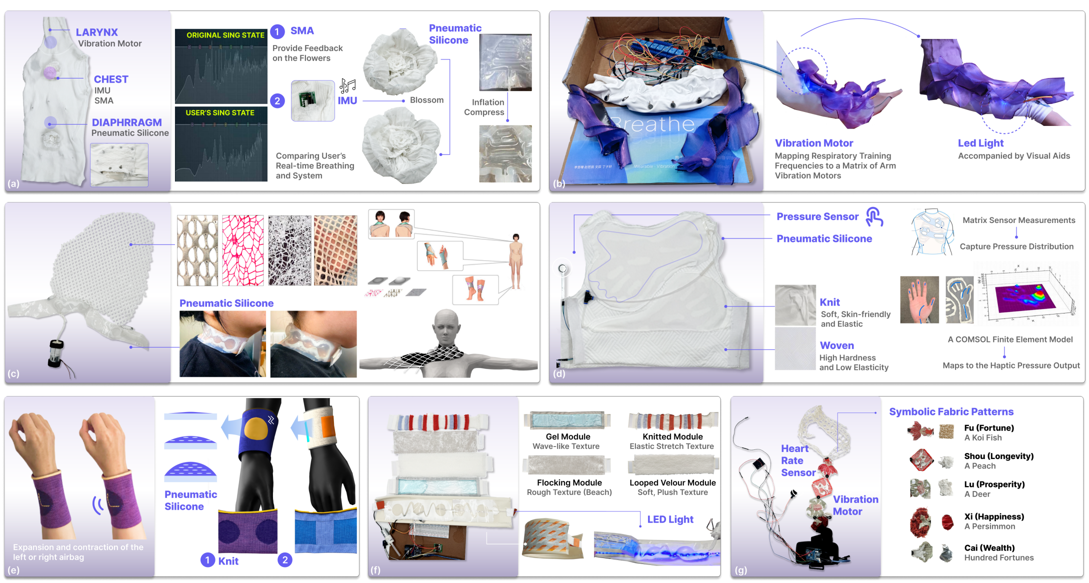

Fig. 5. These group figures provides a detailed explanation of the selection of materials, haptic actuators, and haptic sensations from each group's prototype. From a) to g), each single figure corresponds to Group 1 to Group 7, offering a visualized explanation.

5.2 Effective Wearable Design Process Powered by HaptiFab

5.2.1 The UEQ Result of Workshop. In this stage, the UEQ is employed to evaluate the user experience of the HaptiFab. 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.

Descriptive Statistical Analysis. There are six dimensions in the UEQ: Attractiveness, which constitutes a pure valence dimension; Perspicuity, Efficiency, and Dependability, which represent pragmatic quality aspects (goal-directed); and Stimulation and Novelty, which exemplify hedonic quality aspects (not goal-directed). To assess these dimensions, we conducted descriptive statistical analysis based on responses from 30 participants. The analysis revealed that the participants found the materials in HaptiFab very appealing, particularly noting its usefulness in creating smart haptic interaction prototypes. The values for the six dimensions are: Mean=[1.367, 1.872] and SD=[0.824,1.096]. Overall, the 30 participants found the materials provided in HaptiFab very appealing, significantly aiding in the creation of smart haptic interaction prototypes (M = 1.872, SD = 0.824).

In terms of hedonic qualities, participants rated highly, finding the materials and wearable technology in HaptiFab to be very novel (M = 1.475, SD = 1.075), which greatly stimulated creativity and aided in prototype creation (M = 1.792, SD = 0.974). For the "inferior/valuable" item, 80% of participants rated it above 1, indicating that HaptiFab is highly valuable for haptic prototype design and development. However, in pragmatic qualities, scores related to the creation of smart haptic prototypes were relatively neutral. This was primarily reflected in the clarity of haptic technology (M = 1.367, SD = 1.096), such as "confusing/clear" and "complicated/easy" items, more than 10% of the ratings were below -1, indicating that designers without a technical background may need some time to master HaptiFab. The efficiency of operations during prototype creation (M = 1.45, SD = 0.95), and the reliability of the prototypes in matching their intended functionality (M = 1.433, SD = 0.858). For the "unpredictable/predictable" item, 30% of the ratings were below 0, indicating that the results achieved with HaptiFab do not fully meet users' expectations, and that the design process requires some exploration and adjustment.

Benchmark Data. We compared the results of HaptiFab with benchmark data from 468 studies, and the findings are presented in the bar chart shown in Fig. 6. In six dimensions, the Attractiveness and Stimulation dimensions performed excellently, demonstrating that HaptiFab is more appealing to designers and engineers and effectively supports their design process compared to other products. The Novelty dimension was good, indicating that HaptiFab is creative and innovative. The dimensions of Perspicuity, Efficiency, and Dependability all scored above average. Among these, Perspicuity received relatively lower ratings, suggesting that there is still room for improvement in the toolkit's clarity and technical guidance. These findings aligned with the interview results, as discussed in the subsequent subsections on qualitative data.

5.2.2 Lowering Barriers in Interdisciplinary Context. Many participants (P13, P18, P24) praised HaptiFab for reducing prototyping challenges, particularly in interdisciplinary contexts. They mentioned that it helped them overcome difficulties and successfully develop HCI prototypes. Additionally, the design manual was highlighted as a useful resource (N=23), assisting participants in refining their design ideas and selecting suitable haptic actuators and fabrics. For example, P7, a programmer, stated that the design manual helped integrate team members' perspectives, creating a shared vision between designers and engineers.

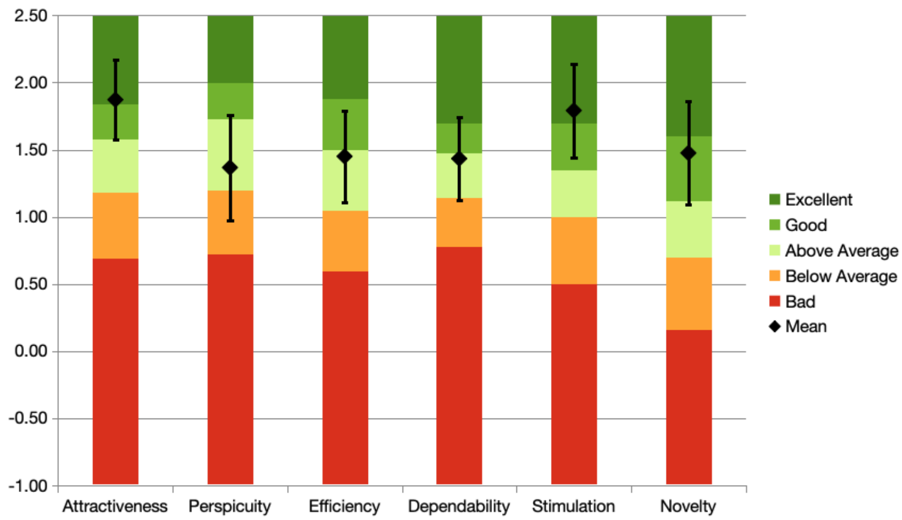

Fig. 6. Comparison of HaptiFab Results with Benchmark Data of UEQ

> *"Although I'm familiar with programming vibration signals, I've rarely completed a full design before. By following the steps in the design manual and brainstorming with my teammates, we could continuously think about how the technology meets user expectations, thus improving our prototype design."*

However, due to the gap between disciplines and the time constraints of the workshop, our quantitative results reported that the benchmark score for perspicuity was relatively low compared to other dimensions. During interviews, we gathered some suggestions for improvement. Some workshop participants offered valuable ideas on how to better bridge the gap between disciplines. For instance, P9 (a programmer) expressed a desire for more detailed explanations about fabrics in our design manual or workshop introduction. She noted: *"What kind of effects can I achieve with specific properties? Can I deconstruct it? Can I weave different fabrics together to create a new form?"* In response to HaptiFab's content, P4 (a non-programmer) suggested that since the target participants include designer and engineers, we could separate programming tools from non-programming tools, creating two distinct sets of components. This modular approach would make it easier for participants to find and use the tools that match their skill level.

5.2.3 Practical Feasibility. HaptiFab proved highly effective in facilitating quick prototype testing and parameter adjustments, which significantly benefited non-professionals (P3, P19, P23). Participants appreciated its user-friendly design, which streamlined the prototyping process and reduced operational complexities. HaptiFab's modular components allowed users to rapidly iterations with different configurations and refine their prototypes.

However, participants did encounter some challenges during the workshop. The inherent physical properties of certain actuators required multiple iterations to achieve optimal results (P3, P4, P7), which might have impacted the efficiency ratings in our UEQ results. For example, the physical properties of Shape Memory Alloy (SMA) occasionally caused issues when interacting with non-elastic woven fabrics, sometimes resulting in the SMA breaking through the material (P1, P2). Additionally, when electrified, the increased temperature from the SMA could become scorching, posing a risk of fabric damage (P2). To address these problems, G1 implemented practical solutions such as using wooden sticks for structural support and integrating heat-insulating silicone tubing to manage temperature effects effectively. These adaptations highlight HaptiFab's flexibility and the participants' resourcefulness in overcoming technical challenges.

5.3 Design Space and Consideration with HaptiFab

We found that participants primarily considered three distinct levels when using HaptiFab. Guided by the design manual, in selecting haptic actuators or fabrics to design various sensations, their focus was on achieving specific *User Goals*: the Aesthetic Level, Sensory Level, and Symbolic Level. In this subsection, we elaborate on their perspectives.

5.3.1 Scenario Level. HaptiFab was shown by participants to be adaptable to a variety of usage scenarios (P17, P26). The selection of scenario levels played a key role in influencing participants' choices of haptic actuators and fabrics during the workshop. Participants designed scenarios that fell into three categories: Functional Wearables (G1, G5), Self-healing Applications (G2, G4, G6, G7), and Educational Exhibits (G3). The choice of these scenarios represented different user groups and behavioral needs, which in turn affected factors such as the contact area and force feedback of the wearable devices.

Guided by the design manual, participants first identified the target user group and usage scenario. They then conducted detailed research on the expectations of these groups before integrating the haptic actuators and fabrics. For example, P11 mentioned,

> *"As a STEM student, I didn't realize the importance of analyzing specific needs based on scenario settings before starting the design prototype...According to the design manual, we first researched the scenario of breathing exercises and found that such exercises typically involve rhythmic patterns. The vibration motor, with its adjustable frequency and amplitude, can create a matrix that is well-suited for this scenario."*

5.3.2 Aesthetic Level. Our participants demonstrated a strong emphasis on aesthetics when integrating fabrics and haptic actuators, highlighting the importance of Visual Metaphor, Symbolic Meaning.

Visual Aesthetics and Metaphor. Participants' aesthetic choices often reflected the thematic elements in their designs. For example, G3 used perforated mesh fabrics that resembled fishing nets to metaphorize ocean pollution (Fig.5 c). P9 explained,

> *"We draped a net-like fabric around the user's neck to create a rough haptic sensation and give the feeling of being trapped in a fishing net. The fabric's open holes and coarse texture were chosen to help users connect with this idea on a sensory level... We also designed round, bubble-like pneumatic silicone, intended to metaphorically represent the bubbles released by sea creatures, aiming to align the visual and haptic sensations for a more immersive experience."*

Similarly, G7 incorporated fabric shaped like goldfish, with the colors metaphorizing traditional Chinese symbols of fortune, prosperity, and longevity (Fig.5 g). These choices highlighted a focus on visual appeal while embedding broader social or cultural metaphors into the designs.

Integration Techniques and Modular Design. A major aesthetic consideration was the seamless integration of haptic actuators within the fabric. Most participants preferred to embed the actuators inside the material rather than exposing them, which enhanced the overall look and feel of the wearables. For instance, G1 concealed the SMA within petal-like structures that blossomed dynamically based on real-time IMU monitoring on the chest area (Fig.5 a). Meanwhile, G4 and G5 secured haptic components between fabric layers, ensuring minimal visual disruption (Fig.5 d, Fig.5 e). To offer richer aesthetic flexibility, G6 and G7 adopted a modular design where haptic actuators were assembled into small, interchangeable modules (Fig. 5 f, g). As P23 described, *"Different fabric materials create varied haptic sensations. Like, flocked fabric feels a bit like the rough texture of a beach, while looped velour gives a soft, plush feeling. We wanted to provide users with a diverse sensory experience, reminiscent of the beach. At the same time, these different fabrics offer distinct visual qualities, so we cut them into modular components, allowing users to swap them out as they like."*

5.3.3 Sensory Level. Participants were highly satisfied with the sensory diversity provided by both the haptic and fabric kits of HaptiFab (P7, P9, P28, P30), noting that the prototypes met their initial expectations for sensory feedback (P7, P28). For example, P17 described their design of a navigation wristband for cyclists: *"We wanted to design a wristband that provides directional prompts while cycling. Since navigation isn't an urgent task, we opted for pneumatic silicon instead of urgent vibration alerts. The pneumatic system well, with clear expansion effects that users could easily feel."* (Fig. 5 e).

However, the sensory design was still influenced by hardware and technical limitations that affected usability. When asked why G5 did not use vibration motors, P17 explained, *"Vibration motors need to be very close to the skin to be felt, whereas pneumatic silicon have noticeable expansion and are easily felt."* Additionally, P18 highlighted the importance of balancing sensory effectiveness with practical implementation limitations in wearable design, noting that vibration motors involve various adjustable parameters such as frequency, amplitude, duration, and matrix configurations, which might be challenging to explore fully within a five-day workshop.

5.3.4 Symbolic Level. Participants place high importance on symbolic meanings when integrating haptic materials with fabrics. G1's design (Fig. 5 a) which combines SMA with mesh to create a flower shape, uses the flower's blooming and closing to Symbolic the opening and closing of a singer's chest cavity during inhalation and exhalation. This design choice effectively links the physical act of singing with a visual symbol, enriching the sensory experience for the wearer. The dynamic movement of the flower visually represents the singing process while also providing haptic feedback, thereby enhancing both the symbolic connection and user engagement with the design. Similarly, G4's design (Fig. 5 d) employs pneumatic silicone shaped like two embracing hands to symbolize a hug. To enhance the realism of this symbol, participants used paint to create handprints on clothing, which were then used to mold the shape of the pneumatic component. As P14 described, *"We aimed to replicate the genuine position of a hug and use the airbag as a symbolic representation of a real embrace, hoping to enhance both realism and comfort."*

5.3.5 Potential Applications and Future Directions from the Workshop. During the initial stages of the workshop, participants brainstormed a variety of meaningful ideas, offering numerous potential applications for HaptiFab in the future.

Emotional Expression. Participants highlighted the potential for combining haptic actuator with fabric to create more emotionally resonant experiences (P11, P16). This aligns with the findings of Kim et al. [10]. For instance, P16 noted that pneumatic silicone could effectively convey the intimacy of a remote hug, offering a more tactile, emotional connection. P6, integrating her professional background, suggests that current electrocardiograms (ECGs) only provide visual sensation, and haptic technology could be used to simulate the heartbeat of deceased loved ones or pets.

Augmented Design. P18 and P23 believe that wearable devices based on VR games can augment human sensations and enhance immersion. For example, SMA can provide a "pulling" sensation. In the future, wearable devices could render haptic data to synchronize with game experiences, as noted by Han et al. (2023) [103]. P9 suggests that combining haptic technology with fabric is well-suited for inclusive design:

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

P12 suggested that integrating pneumatic silicone into clothing could provide injury prevention, particularly for high-risk activities. Inspired by fall-prevention designs for the elderly [104], she proposed adapting this technology for skiers, who frequently experience falls during training and therefore require more targeted protection.

Therapeutic and Assistive Applications. Beyond wearables, participants envisioned using these HaptiFab 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 the development of haptic robots capable of precise grip force measurement and weight-bearing functions. P17 further suggested that SMA could serve as actuators for soft robotics, expanding their functionality in both medical and industrial applications.

6 SYSTEMATIC WORKFLOW FOR INTEGRATING HAPTIC ACTUATORS WITH FABRIC IN INTERDISCIPLINARY DESIGN

Integration of Haptic Actuator and Fabric Based on the quantitative and qualitative analysis from our workshop, the design manual has demonstrated its ability to guide users in optimizing their design thinking (P7) and supporting decision-making processes (P12), enabling users to quickly become proficient with HaptiFab. Therefore, following the three phases in the design manual, we propose a systematic workflow illustrated in Fig. 7. This workflow is designed to help designers and engineers systematically integrate theoretical approaches, facilitating interdisciplinary collaboration and fostering synergy between different fields [105]. By integrating design and technical aspects, this workflow aims to better address actual user needs, enabling them to make more informed choices when combining haptic actuators with fabric.

6.1 Systematic Workflow Overview and Process

As an interdisciplinary field, HCI requires careful consideration of how to integrate technology and design effectively [85]. Drawing on the framework proposed by Zimmerman et al., we incorporate "Research through Design" into HCI research, focusing on three key elements: Behavioral Scientists (True), Anthropologists (Real), and Engineers (How) [28]. Our work emphasizes the integration of haptic actuators and fabric for interdisciplinary design in wearable toolkits, forming a cyclic workflow, as shown in Fig.7.

Feedback Loop. The workflow forms a loop, starting with scenario exploration, followed by data input, haptic and fabric parameter adjustment, sensory output, and finally user feedback. This cyclical process ensures that designs continuously evolve based on user needs and interdisciplinary insights.

Behavioral Scientists (True). The first step is defining the scenario. These scenarios may include daily life activities such as education, work, recreation, and public environments. Through thorough research on the target user's behavior and pain points within these contexts, user expectations can be derived. These expectations address questions (e.g., Who? What? Why? When? Where? How? and even How much?) are crucial factors in shaping the user's needs and goals. The ultimate aim is to determine what kind of sensory experiences the users are expected to feel and how these sensations can address specific problems or challenges (e.g., passive, rough feelings).

Anthropologists (Real). Once the user's behaviors and needs are understood, it's essential to identify which data is appropriate for input. This stage involves collecting user-specific data, such as behavior patterns, physiological responses, and environmental factors, feeding directly into the engineering design process. The wearable haptic experience is then tailored to specific areas of the body, with positions of contact defined (as illustrated in Fig.7) to ensure precise body part selection for sensation application.

Engineers (How). After establishing the design strategy, it is crucial to select the appropriate haptic actuator and fabric parameters that match the user's expectations and the wearable scenario. For haptic actuators, this involves parameters like force feedback and contact area, while for fabrics, haptic perception factors such as softness or roughness, smoothness or coarseness are considered. Additionally, the integration of haptic actuators with fabrics must be carefully addressed, including the selection of the integration method (e.g., point contact, partial wrapping, or full wrapping).

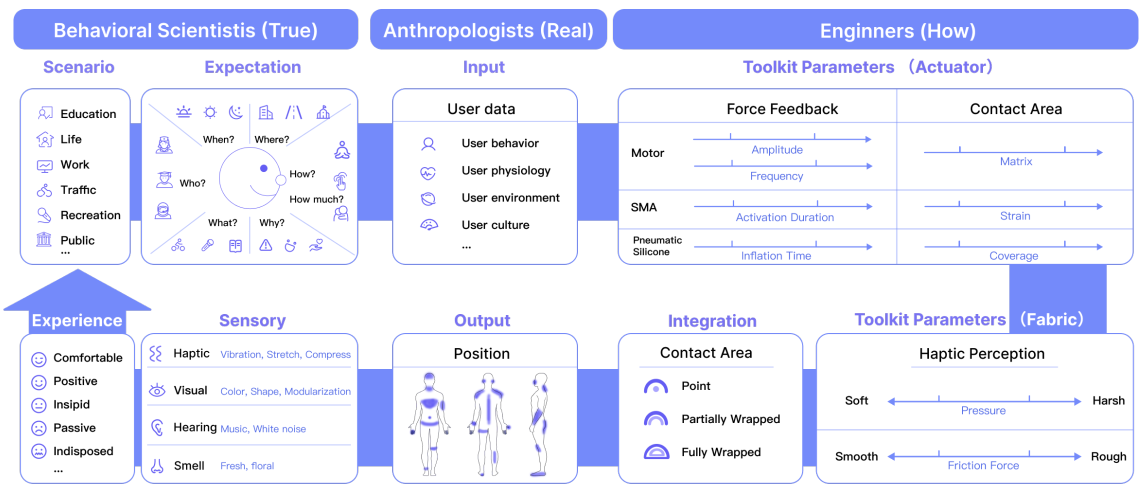

Fig. 7. Systematic Workflow

To assess the effectiveness of our systematic workflow, we aligned it with the prototype cases developed during the workshop. Designers and engineers from various disciplines were able to follow the process smoothly, receiving clear guidance that enhanced both efficiency and design precision. The specific workflows for each group are detailed in Fig. 8. Overall, our workflow demonstrates its ability to help interdisciplinary teams integrate haptic actuators and fabrics in the design of wearable technologies.

7 DISCUSSION

7.1 Exploring the Design Space of HaptiFab

Haptic Actuator as A Core Element in Wearable Technology. Haptic feedback in wearable technology extends beyond devices like smartwatches. HaptiFab demonstrates broader applications by enabling the integration of more diverse and functional haptic devices. Our participants typically prioritized the interaction capabilities of haptic actuators during

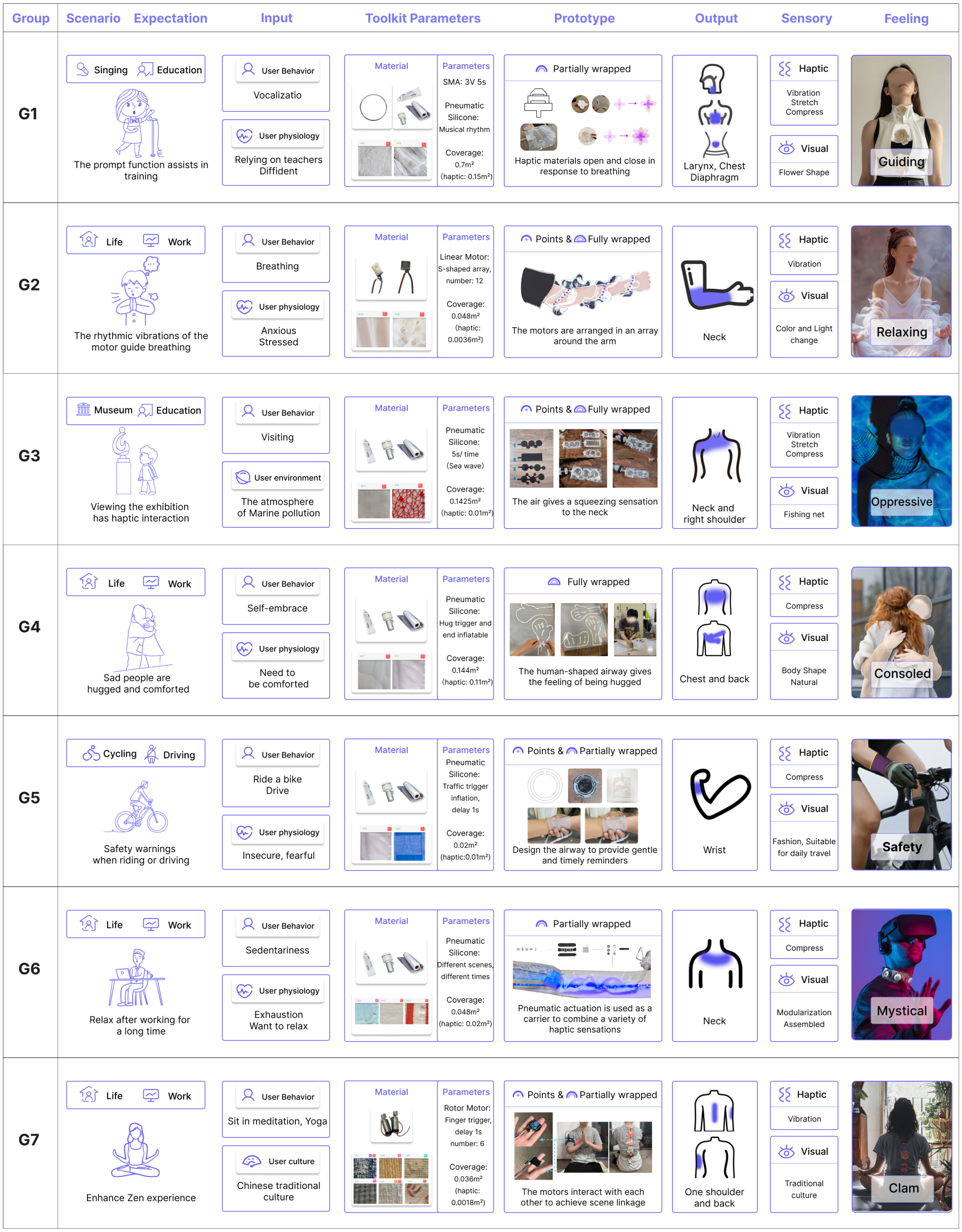

Fig. 8. Mapping with Workshop Case to Evaluating Systematic Workflow

prototyping, with fabric serving primarily as a carrier for wearability. The effectiveness of these actuators depends on factors such as body placement, actuator characteristics, and parameter design. However, the ease of use still requires improvement, as participants noted the need for iterations and testing to achieve optimal results (P3, P4), and there is still room for improvement in terms of convenience. In this regard, our toolkit could incorporate a more streamlined and integrated software platform (P18), allowing users to adjust factors that influence the haptic actuators based on the desired functionality during the prototyping process. Features such as LayTex [106] and O&O [31] would enable users to visualize the haptic simulations effectively.

Simplifying Access to Prototyping and Innovation. Our workshop findings show that HaptiFab significantly reduces the technical and design complexities involved in integrating haptic actuators with fabric. The toolkit provides DIY-friendly, easily accessible, and cost-effective tools (P18, P26) that lower the learning barrier, allows rapid prototyping and encourages innovation. By making wearable technology more accessible, HaptiFab empowers designers and engineers to explore innovative possibilities for creating interactive experiences across disciplines. Moreover, participants also envisioned broader applications beyond wearables, including tangible toys (P6), therapeutic devices (P14, P25, P7), and sleep aids (P8). These insights suggest a wide, relatively unexplored design space with exciting possibilities for future research and development, empowering designers and engineers to create interactive experiences across various disciplines.

7.2 Enhancing Flexibility and Creative through Interdisciplinary Collaboration

Building on insights from our workshop, we have refined our design manual and developed a systematic workflow for integrating haptic actuator and fabric into wearable technology. HaptiFab provides considerable flexibility, enabling designers and engineers to tailor prototypes to diverse scenarios, user expectations, and data inputs. Its DIY-friendly design further supports adjustable parameters, allowing customization of haptic output, sensory feedback, and overall user experience. Compared to other haptic toolkits [30], HaptiFab offers enhanced creative freedom [31], which aids interdisciplinary teams in aligning their shared vision for prototypes [107]. This workflow, which integrates design thinking and HCI principles [28], provides clear guidance for merging technical and design perspectives. It offers a more structured approach than other interdisciplinary frameworks [84], addressing three key challenges in haptic-fabric integration: a) inconsistencies in project foundations, b) differing interpretations of terminology, and c) methodological disparities [107]. By addressing these challenges, we aim to encourage more interdisciplinary teams to explore the potential of integrating haptic actuators and fabric, contributing to advancements in wearable technology.

7.3 Limitations and Future Work

Our findings indicate that in interviews with all seven teams, participants encountered minimal barriers when selecting fabrics. This ease is likely due to their frequent use of fabrics in daily life, which reduces the need for additional learning. However, selecting haptic actuators faced challenges, as participants had to go through multiple iterations to identify the most suitable options. The inherent physical properties of certain actuators (P3,P4), such as the heat generation of Shape Memory Alloy (SMA), and the overall ease of use influenced their preferences. Consequently, five teams chose pneumatic silicon for their prototypes. In contrast, only one team used Shape Memory Alloy (SMA), which resulted in limited exploration of SMA. Moreover, the 5-day workshop duration limited the time available for thorough experimentation with each haptic parameter. Participants also experienced cognitive load when working with new materials [93]. To address these issues, it would be beneficial to develop more detailed and user-friendly toolkit guidelines. Providing comprehensive information on haptic parameters and cases of haptic-fabric integration could facilitate faster prototyping and support a more extensive exploration of various haptic actuators.

Additionally, while each group successfully achieved their 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 need for multiple PWM (pulse-width modulation) signals to drive the vibration motor matrix, which was constrained by the limited PWM output channels of HaptiFab's Electronic Modules. As a result, the constraints of the existing Arduino hardware kits, which have a fixed number of modules, led to unnecessary spatial limitations. To address these issues, future work should focus on developing and customizing driver modules that better meet the needs of HaptiFab. Such modules should offer greater flexibility and scalability to accommodate complex vibration control requirements [22, 42]. By optimizing the design of these driver modules, we can enhance the overall performance and adaptability of the system.

Our future work is divided into two main areas. (1) Address the limitations of the current Electronic Modules hardware by developing supplementary components specifically designed to better supports our three types of haptic actuators. This includes creating custom PWM modules or other hardware enhancements to ensure more efficient control and integration of these actuators. (2) Refine the HaptiFab parameters within the systematic workflow. This involves developing a pre-programming library for our haptic and fabric kits, which will allow users to set fixed parameters and content within the software. For more skilled designers or engineers, this library will offer advanced customization options, while for general users, we will design more intuitive software interfaces. We also propose integrating existing research on various haptic effects, such as vibration motors and their impact on user arousal, into HaptiFab. This integration will enable the software to recommend suitable haptic generation parameters based on the user's design scenarios and expectations, thereby aiding the design process. As users explore, the integration of fabric and haptic actuators can extend beyond wearable technology to a wide range of products and installations. Investigating this design space is significant, as it offers potential applications across diverse contexts and usage scenarios.

8 CONCLUSION

In this paper, we present HaptiFab, a Wearable Toolkit supports Haptic actuator and Fabric Integration for interdisciplinary DIY design, is designed to assist designers and engineers in balancing both technical and design aspects during prototype creation. HaptiFab consists of three modules: a) Haptic Generation Kit, b) Fabric Kit, and c) Design Manual. With the guidance of the design manual, engineers and designers without prior haptic experience can quickly create and develop prototypes. We conducted a workshop with 30 participants, resulting in 7 prototype collections. Through interviews with participants, we found that HaptiFab is user-friendly and effectively conveys the desired haptic effects through DIY methods. Based on insights from the workshop, we refined the design manual and developed a systematic workflow for integrating haptic actuators with fabric in interdisciplinary design. This workflow aims to guide users in the development of haptic wearable devices and facilitate their broader DIY application in the future.

References

[1] Mohamad A Eid and Hussein Al Osman. Affective haptics: Current research and future directions. *IEEE Access*, 4:26–40, 2015.

[2] Shantonu Biswas and Yon Visell. Haptic perception, mechanics, and material technologies for virtual reality. *Advanced Functional Materials*, 31(39):2008186, 2021.

[3] Matteo Bianchi. A fabric-based approach for wearable haptics. *Electronics*, 5(3):44, 2016.

[4] Andrew A. Stanley and Katherine J. Kuchenbecker. Design of body-grounded tactile actuators for playback of human physical contact. In *2011 IEEE World Haptics Conference*, pages 563–568, 2011.

[5] Max Pfeiffer, Tim Duente, and Michael Rohs. Let your body move: a prototyping toolkit for wearable force feedback with electrical muscle stimulation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '16, page 418–427, New York, NY, USA, 2016. Association for Computing Machinery.

[6] Qian Qiu, Miaomiao Zhu, Zhaoling Li, Kaili Qiu, Xiaoyan Liu, Jianyong Yu, and Bin Ding. Highly flexible, breathable, tailorable and washable power generation fabrics for wearable electronics. *Nano Energy*, 58:750–758, 2019.

[7] Jianfeng Wen, Bingang Xu, Yuanyuan Gao, Meiqi Li, and Hong Fu. Wearable technologies enable high-performance textile supercapacitors with flexible, breathable and wearable characteristics for future energy storage. *Energy Storage Materials*, 37:94–122, 2021.

[8] Melkie Getnet Tadesse, Carmen Loghin, Ionuț Dulgheriu, and Emil Loghin. Comfort evaluation of wearable functional textiles. *Materials*, 14(21):6466, 2021.

[9] Ruiqing Li, Yeyang Wang, Yujie Chen, Jiaxuan Zhao, Yawei Wang, J. An, Yanan Lu, Yuehua Chen, Wenyong Lai, Xinwen Zhang, and Wei Huang. Efficient flexible fabric-based top-emitting polymer light-emitting devices for wearable electronics. *Small*, pages e2305327–e2305327, 2023.

[10] Jin Hee (Heather) Kim, Kunpeng Huang, Simone White, Melissa Conroy, and Cindy Hsin-Liu Kao. Knitdermis: Fabricating tactile on-body interfaces through machine knitting. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference*, DIS '21, page 1183–1200, New York, NY, USA, 2021. Association for Computing Machinery.

[11] Jing Xue, Bruna Beatriz Petreca, Christopher Dawes, and Marianna Obrist. Fabtouch: A tool to enable communication and design of tactile and affective fabric experiences. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pages 1–16, 2023.

[12] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers. Springlets: Expressive, flexible and silent on-skin tactile interfaces. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, page 1–14, New York, NY, USA, 2019. Association for Computing Machinery.

[13] Kyle T. Yoshida, Cara M. Nunez, Sophia R. Williams, Allison M. Okamura, and Ming Luo. 3-dof wearable, pneumatic haptic device to deliver normal, shear, vibration, and torsion feedback. In *2019 IEEE World Haptics Conference (WHC)*, pages 97–102, 2019.

[14] Janelle P Clark, Sung Y Kim, and Marcia K O'Malley. The rice haptic rocker: Comparing longitudinal and lateral upper-limb skin stretch perception. In *Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part II 11*, pages 125–134. Springer, 2018.

[15] B Holschuh and D Newman. Two-spring model for active compression textiles with integrated niti coil actuators. *Smart Materials and Structures*, 24(3):035011, 2015.

[16] Svetlana Yarosh, Kenya Mejia, Baris Unver, Xizi Wang, Yuan Yao, Akin Campbell, and Brad Holschuh. Squeezebands: Mediated social touch using shape memory alloy actuation. *Proc. ACM Hum.-Comput. Interact.*, 1(CSCW), dec 2017.

[17] Mengjia Zhu, Amirhossein H. Memar, Aakar Gupta, Majed Samad, Priyanshu Agarwal, Yon Visell, Sean J. Keller, and Nicholas Colonnese. Pneusleeve: In-fabric multimodal actuation and sensing in a soft, compact, and expressive haptic sleeve. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–12, New York, NY, USA, 2020. Association for Computing Machinery.

[18] Trevor L. Buckner, R. Adam Bilodeau, Sang Yup Kim, and Rebecca Kramer-Bottiglio. Roboticizing fabric by integrating functional fibers. *Proceedings of the National Academy of Sciences*, 117(41):25360–25369, 2020.

[19] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. Hapticclench: Investigating squeeze sensations using memory alloys. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, page 109–117, New York, NY, USA, 2017. Association for Computing Machinery.

[20] Marcelo Coelho and Pattie Maes. Sprout i/o: a texturally rich interface. In *Proceedings of the 2nd international conference on Tangible and embedded interaction*, pages 221–222, 2008.

[21] Massimiliano Solazzi, William R Provancher, Antonio Frisoli, and Massimo Bergamasco. Design of a sma actuated 2-dof tactile device for displaying tangential skin displacement. In *2011 IEEE World Haptics Conference*, pages 31–36. IEEE, 2011.

[22] Gijs Huisman and Aduén Darriba Frederiks. Towards tactile expressions of emotion through mediated touch. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '13, page 1575–1580, New York, NY, USA, 2013. Association for Computing Machinery.

[23] Leonardo Bonanni, Cati Vaucelle, Jeff Lieberman, and Orit Zuckerman. Taptap: a haptic wearable for asynchronous distributed touch therapy. In *CHI'06 extended abstracts on Human factors in computing systems*, pages 580–585, 2006.

[24] Kristina Hook. *Designing with the body: Somaesthetic interaction design.* MIt Press, 2018.

[25] Martijn ten Bhömer, Ruggero Canova, and Eva de Laat. Body inspired design for knitted body-protection wearables. In *Proceedings of the 2018 ACM Conference Companion Publication on Designing Interactive Systems*, DIS '18 Companion, pages 135–139, New York, NY, USA, 2018. Association for Computing Machinery.

[26] Hayes Solos Raffle, Amanda J. Parkes, and Hiroshi Ishii. Topobo: a constructive assembly system with kinetic memory. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '04, page 647–654, New York, NY, USA, 2004. Association for Computing Machinery.

[27] Masashi Konyo, Hiroshi Yamada, Shogo Okamoto, and Satoshi Tadokoro. Alternative display of friction represented by tactile stimulation without tangential force. In *Haptics: Perception, Devices and Scenarios: 6th International Conference, EuroHaptics 2008 Madrid, Spain, June 10-13, 2008 Proceedings 6*, pages 619–629. Springer, 2008.

[28] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. Research through design as a method for interaction design research in hci. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 493–502, 2007.

[29] Evan Pezent, Marcia K. O'Malley, Ali Israr, Majed Samad, Shea Robinson, Priyanshu Agarwal, Hrvoje Benko, and Nicholas Colonnese. Explorations of wrist haptic feedback for ar/vr interactions with tasbi. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI EA '20, page 1–4, New York, NY, USA, 2020. Association for Computing Machinery.

[30] Qi Wang, Yuan Zeng, Runhua Zhang, Nianding Ye, Linghao Zhu, Xiaohua Sun, and Teng Han. Emtex: Prototyping textile-based interfaces through an embroidered construction kit. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*, pages 1–17, 2023.

[31] Yuxuan Lei, Qi Lu, and Yingqing Xu. O&o: A diy toolkit for designing and rapid prototyping olfactory interfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, pages 1–21, 2022.

[32] Shreyosi Endow, Hedieh Moradi, Anvay Srivastava, Esau G Noya, and Cesar Torres. Compressables: A haptic prototyping toolkit for wearable compression-based interfaces. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference*, DIS '21, page 1101–1114, New York, NY, USA, 2021. Association for Computing Machinery.

[33] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. Squeezeback: Pneumatic compression for notifications. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, page 5318–5330, New York, NY, USA, 2017. Association for Computing Machinery.

[34] Sida Dai, Brygg Ullmer, and Winifred Elysse Newman. Morphmatrix: A toolkit facilitating shape-changing interface design. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '24, New York, NY, USA, 2024. Association for Computing Machinery.

[35] Liang He, Cheng Xu, Ding Xu, and Ryan Brill. Pneuhaptic: delivering haptic cues with a pneumatic armband. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers*, ISWC '15, page 47–48, New York, NY, USA, 2015. Association for Computing Machinery.

[36] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. Hapticclench: Investigating squeeze sensations using memory alloys. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, page 109–117, New York, NY, USA, 2017. Association for Computing Machinery.

[37] Marcelo Coelho and Pattie Maes. Sprout i/o: a texturally rich interface. In *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction*, TEI '08, page 221–222, New York, NY, USA, 2008. Association for Computing Machinery.

[38] Yosuke Mizukami and Hideyuki Sawada. Tactile information transmission by apparent movement phenomenon using shape-memory alloy device. *International Journal on Disability and Human Development*, 5(3):277–284, 2006.

[39] Rachael Granberry, Kevin Eschen, Brad Holschuh, and Julianna Abel. Functionally graded knitted actuators with niti-based shape memory alloys for topographically self-fitting wearables. *Advanced materials technologies*, 4(11):1900548, 2019.

[40] Hussein FM Ali and Youngshik Kim. Design procedure and control of a small-scale knee exoskeleton using shape memory alloy springs. *Microsystem Technologies*, 29(8):1225–1234, 2023.

[41] Budiman Salam and Rachel Lee Siew Tan. Stretchability of electronic components assembled on fabric for wearable electronics applications, 2023.

[42] Kelly Dobson, Danah Boyd, Wendy Ju, Judith Donath, and Hiroshi Ishii. Creating visceral personal and social interactions in mediated spaces. In *CHI'01 Extended Abstracts on Human Factors in Computing Systems*, pages 151–152, 2001.

[43] Alice Haynes, Melanie F. Simons, Tim Helps, Yuichi Nakamura, and Jonathan Rossiter. A wearable skin-stretching tactile interface for human–robot and human–human communication. *IEEE Robotics and Automation Letters*, 4(2):1641–1646, 2019.

[44] Henning Pohl, Dennis Becke, Eugen Wagner, Maximilian Schrapel, and Michael Rohs. Wrist compression feedback by pneumatic actuation. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '15, page 315–318, New York, NY, USA, 2015. Association for Computing Machinery.

[45] Susan J Lederman and Roberta L Klatzky. Haptic perception: A tutorial. *Attention, Perception, & Psychophysics*, 71(7):1439–1459, 2009.

[46] Ramiro Velazquez, Edwige E Pissaloux, Moustapha Hafez, and Jérôme Szewczyk. Tactile rendering with shape-memory-alloy pin-matrix. *IEEE Transactions on Instrumentation and Measurement*, 57(5):1051–1057, 2008.

[47] Parris S Wellman, William J Peine, Gregg Favalora, and Robert D Howe. Mechanical design and control of a high-bandwidth shape memory alloy tactile display. In *Experimental Robotics V: The Fifth International Symposium Barcelona, Catalonia, June 15–18, 1997*, pages 56–66. Springer, 1998.

[48] Qiaolian Xie, Qiaoling Meng, Wenwei Yu, Rongna Xu, Zhiyu Wu, Xiaoming Wang, and Hongliu Yu. Design of a soft bionic elbow exoskeleton based on shape memory alloy spring actuators. *Mechanical Sciences*, 14(1):159–170, 2023.

[49] Kevin Eschen, Rachael Granberry, Bradley Holschuh, and Julianna Abel. Amplifying and leveraging generated force upon heating and cooling in sma knitted actuators. *ACS Applied Materials & Interfaces*, 12(48):54155–54167, 2020.

[50] Bradley T Holschuh and Dava J Newman. Morphing compression garments for space medicine and extravehicular activity using active materials. *Aerospace medicine and human performance*, 87(2):84–92, 2016.

[51] Qiang Liu, Sepideh Ghodrat, Gijs Huisman, and Kaspar M.B. Jansen. Shape memory alloy actuators for haptic wearables: A review. *Materials Design*, 233:112264, 2023.

[52] Qi Wang, Marina Toeters, Wei Chen, Annick Timmermans, and Panos Markopoulos. Zishi: A smart garment for posture monitoring. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '16, page 3792–3795, New York, NY, USA, 2016. Association for Computing Machinery.

[53] Masahiro Miyakami, Karen. A. Murata, and Hiroyuki Kajimoto. *Hapballoon: Wearable Haptic Balloon-Based Feedback Device*, page 17–18. Association for Computing Machinery, New York, NY, USA, 2019.

[54] J. Berzowska and M. Coelho. Kukkia and vilkas: kinetic electronic garments. In *Ninth IEEE International Symposium on Wearable Computers (ISWC'05)*, pages 82–85, 2005.

[55] Min-Woo Han and Sung-Hoon Ahn. Blooming knit flowers: Loop-linked soft morphing structures for soft robotics. *Advanced Materials (Deerfield Beach, Fla.)*, 29(13), 2017.

[56] Soo-Min Lee and Juyeon Park. A soft wearable exoglove for rehabilitation assistance: a novel application of knitted shape-memory alloy as a flexible actuator. *Fashion and Textiles*, 11(1):14, 2024.

[57] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. Morphees: toward high" shape resolution" in self-actuated flexible mobile devices. In *Proceedings of the SIGCHI conference on human factors in computing systems*, pages 593–602, 2013.

[58] Joohee Park, Young-Woo Park, and Tek-Jin Nam. Wrigglo: shape-changing peripheral for interpersonal mobile communication. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, page 3973–3976, New York, NY, USA, 2014. Association for Computing Machinery.

[59] Li Liu, Ruomei Wang, Zhuo Su, Xiaonan Luo, and Chengying Gao. Mesh-based anisotropic cloth deformation for virtual fitting. *Multimedia Tools and Applications*, 71(2):411–433, 2014.

[60] Luisa von Radziewsky, Antonio Krüger, and Markus Löchtefeld. Scarfy: Augmenting human fashion behaviour with self-actuated clothes. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, page 313–316, New York, NY, USA, 2015. Association for Computing Machinery.

[61] Soo-Min Lee, Gyomyung Shin, Hyucksoon Im, Midum Oh, Sofia Castro Avalos, Mi-Jeong Yoon, Joon-Sung Kim, Juyeon Park, and Sung-Hoon Ahn. Feasibility of a warp-knitted shape memory alloy rehabilitation glove. *Journal of Industrial Textiles*, 54:15280837241238446, 2024.

[62] Joanna Berzowska and Di Mainstone. Skorpions: kinetic electronic garments. In *ACM SIGGRAPH 2008 talks*, pages 1–1. 2008.

[63] Laura Perovich, Philippa Mothersill, and Jennifer Broutin Farah. Awakened apparel: embedded soft actuators for expressive fashion and functional garments. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*, pages 77–80, 2014.

[64] Kentaro Ueda, Tsutomu Terada, and Masahiko Tsukamoto. Input interface using wrinkles on clothes. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers*, ISWC '16, page 56–57, New York, NY, USA, 2016. Association for Computing Machinery.

[65] Kentaro Ueda, Tsutomu Terada, and Masahiko Tsukamoto. Input interface using wrinkles on clothes for wearable computing. *Journal of Information Processing*, 27:96–105, 2019.

[66] Xinyu Guo, Wenbo Li, Fuyi Fang, Huyue Chen, Linchuan Zhao, Xiaoyong Fang, Zhiran Yi, Lei Shao, Guang Meng, and Wenming Zhang. Encoded sewing soft textile robots. *Science Advances*, 10(1):eadk3855, 2024.

[67] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. Foldio: Digital fabrication of interactive and shape-changing objects with foldable printed electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, page 223–232, New York, NY, USA, 2015. Association for Computing Machinery.

[68] First Authors Last and First Another. Neuro-perceptive discrimination on fabric tactile stimulation by electroencephalographic (eeg) spectra. *PLOS ONE*, Volume(Issue):Page Range, Year.

[69] Lei Chen, Zhijun Zhang, and Jian Fan. Investigation on tactile properties of fabrics based on physical and surface properties. *The Journal of the Textile Institute*, 104(8):808–815, 2013.

[70] Emilie Bertaux, Maryline Lewandowski, and Siegfried Derler. Relationship between friction and tactile properties for woven and knitted fabrics. *Textile Research Journal*, 77(6):387–396, 2007.

[71] J. Berzowska and M. Coelho. Kukkia and vilkas: kinetic electronic garments. In *Ninth IEEE International Symposium on Wearable Computers (ISWC'05)*, pages 82–85, 2005.

[72] Yvonne YF Chan Vili. Investigating smart textiles based on shape memory materials. *Textile Research Journal*, 77(5):290–300, 2007.

[73] Jinlian Hu, Mohammad Irfan Iqbal, and Fengxin Sun. Wool can be cool: water-actuating woolen knitwear for both hot and cold. *Advanced Functional Materials*, 30(51):2005033, 2020.

[74] R. Paradiso, G. Loriga, and N. Taccini. A wearable health care system based on knitted integrated sensors. *IEEE Transactions on Information Technology in Biomedicine*, 9(3):337–344, 2005.

[75] Rachael Granberry, Kevin Eschen, Brad Holschuh, and Julianna Abel. Functionally graded knitted actuators with niti-based shape memory alloys for topographically self-fitting wearables. *Advanced materials technologies*, 4(11):1900548, 2019.

[76] Beyza Bozali, Sepideh Ghodrat, Linda Plaude, Joris JF van Dam, and Kaspar MB Jansen. Development of low hysteresis, linear weft-knitted strain sensors for smart textile applications. *Sensors*, 22(19):7688, 2022.

[77] Lea Albaugh, Scott Hudson, and Lining Yao. Digital fabrication of soft actuated objects by machine knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–13, 2019.

[78] Suebin Lee, Helen Koo, and Jasmine Zhou. Fleurtech: Transformable smart dress. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, pages 491–494, 2016.

[79] Stefanie Schaack, George Chernyshov, Kirill Ragozin, Benjamin Tag, Roshan Peiris, and Kai Kunze. Haptic collar: Vibrotactile feedback around the neck for guidance applications. In *Proceedings of the 10th Augmented Human International Conference 2019*, AH2019, New York, NY, USA, 2019. Association for Computing Machinery.

[80] Shreyosi Endow, Hedieh Moradi, Anvay Srivastava, Esau G Noya, and Cesar Torres. Compressables: A haptic prototyping toolkit for wearable compression-based interfaces. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference*, DIS '21, page 1101–1114, New York, NY,

USA, 2021. Association for Computing Machinery.

[81] Harshika Jain, Kexin Lu, and Lining Yao. Hydrogel-based diy underwater morphing artifacts: A morphing and fabrication technique to democratize the creation of controllable morphing 3d underwater structures with low-cost, easily available hydrogel beads adhered to a substrate. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference*, pages 1242–1252, 2021.

[82] Hyunyoung Kim, Aluna Everitt, Carlos Tejada, Mengyu Zhong, and Daniel Ashbrook. Morpheesplug: A toolkit for prototyping shape-changing interfaces. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–13, 2021.

[83] Christoffer Eriksson. *Supporting Caring Touch: A toolkit for sensitizing soma designers through subtle disruptions*. PhD thesis, KTH Royal Institute of Technology, 2023.

[84] Peter Wehrspann and Lois Frankel. Interdisciplinary design: The need for collaboration to foster technological innovation to create competitive and sustainable products. 2010.

[85] John Zimmerman and Jodi Forlizzi. Research through design in hci. In *Ways of Knowing in HCI*, pages 167–189. Springer, 2014.

[86] Alan M Rugman and Joseph R D'cruz. The" double diamond" model of international competitiveness: The canadian experience. *MIR: Management International Review*, pages 17–39, 1993.

[87] John S Gero. Design prototypes: a knowledge representation schema for design. *AI magazine*, 11(4):26–26, 1990.

[88] John S Gero. Design prototypes: a knowledge representation schema for design. *AI magazine*, 11(4):26–26, 1990.

[89] Mustafa C Kutlu. *A home-based functional electrical stimulation system for upper-limb stroke rehabilitation*. PhD thesis, University Of Southampton, 2017.

[90] Hasso Plattner, Christoph Meinel, and Larry Leifer. *Design Thinking Research: Making Design Thinking Foundational*. Understanding Innovation. Springer, 2016.

[91] Don Norman. *Emotional design: Why we love (or hate) everyday things*. Basic books, 2007.

[92] James J Gibson. *The ecological approach to visual perception: classic edition*. Psychology press, 2014.

[93] John Sweller. Cognitive load during problem solving: Effects on learning. *Cognitive science*, 12(2):257–285, 1988.

[94] MG Gee, P Tomlins, A Calver, RH Darling, and M Rides. A new friction measurement system for the frictional component of touch. *Wear*, 259(7-12):1437–1442, 2005.

[95] Bart Gommers, Ignace Verpoest, and Paul Van Houtte. Modelling the elastic properties of knitted-fabric-reinforced composites. *Composites science and technology*, 56(6):685–694, 1996.

[96] Interaction Design Foundation, Rikke Friis Dam, and Teo Yu Siang. What is design thinking and why is it so popular?, 2021.

[97] Martin Schrepp, Jörg Thomaschewski, and Andreas Hinderks. Construction of a benchmark for the user experience questionnaire (ueq). 2017.

[98] Virginia Braun and Victoria Clarke. *Thematic analysis*. American Psychological Association, 2012.

[99] Meg Stuart, A Bulent Turman, Jacqueline Shaw, Natalie Walsh, and Vincent Nguyen. Effects of aging on vibration detection thresholds at various body regions. *BMC geriatrics*, 3:1–10, 2003.

[100] KC Parsons and MJ Griffin. Whole-body vibration perception thresholds. *Journal of sound and Vibration*, 121(2):237–258, 1988.

[101] Sidney Weinstein. Fifty years of somatosensory research: from the semmes-weinstein monofilaments to the weinstein enhanced sensory test. *Journal of Hand therapy*, 6(1):11–22, 1993.

[102] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. aeromorph-heat-sealing inflatable shape-change materials for interaction design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 121–132, 2016.

[103] Violet Yinuo Han, Abena Boadi-Agyemang, Yuyu Lin, David Lindlbauer, and Alexandra Ion. Parametric haptics: Versatile geometry-based tactile feedback devices. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*, pages 1–13, 2023.

[104] Han Chen, Shuqun Wang, Wanrou Tan, and Jie Luo. Stm32-based anti-fall smart vest system for the elderly. In *2022 IEEE 6th Information Technology and Mechatronics Engineering Conference (ITOEC)*, volume 6, pages 516–520. IEEE, 2022.

[105] Celina Retz, Axel Braun, Thomas J Klotzbier, Sabiha Ghellal, and Nadja Schott. Towards co-creative interdisciplinary exergame design processes: A theory-based approach of a vr-exergame fall prevention training. In *Companion Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, pages 69–75, 2023.

[106] Yueyao Zhang, Nianchong Qu, Runhua Zhang, Ye Tao, Guanyun Wang, and Qi Wang. Laytex: A design tool for generating customized textile sensor layouts in wearable computing. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing*, pages 63–67, 2023.

[107] Fiona Maciver, Julian Malins, Julia Kantorovich, and Aggelos Liapis. United we stand: A critique of the design thinking approach in interdisciplinary innovation. 2016.

A Appendix 1

A.1 Question list

Semi-Structured Interview This appendix presents a summary of the semi-structured interviews conducted which is shown in Table.3 to gather insights on the usage and effectiveness of the HaptiFab, the integration of haptic actuator and fabric for interdisciplinary design. The key topics covered include the role of the HaptiFab in the interdisciplinary design process, the benefits of integrating haptic actuator and fabric, and challenges faced in interdisciplinary collaboration.

Table 3. 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 actuations, 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?
Interdisciplinary Design Process	1. What were the challenges you faced while working on an interdisciplinary design program? How did you overcome them? 2. How did your design manual contribute to navigating these challenges? Was it helpful?
User Experience and Evaluation	1. How would you describe the user experience of interacting with the Integration of Haptic Actuator and Fabric, compared to more traditional actuators or fabrics? 2. How did you evaluate the impact of haptic materials on user experience? Did you conduct user testing or gather feedback? What was the result?
Future Prospects	1. What do you see as unexplored opportunities for the Integration of Haptic Actuator and Fabric in the future? How could they be combined with other materials to enhance user experiences? 2. If you were to redesign this program, what changes would you make, or what new ideas would you like to explore?
Additional Insights	1. Are there any additional design or research considerations that you would like to share, such as material choices, fabrication processes, or new wearable technologies? 2. Given the chance to redo the program, what changes or new approaches would you consider?

B Appendix 2

B.1 User Experience Questionnaire

In this program, the UEQ (as shown in Table.4) is employed to evaluate the user experience of the HaptiFab. The results of the questionnaire will help us understand the users' intuitive reactions to the wearable technology and guide the Integration of Haptic Actuator and Fabric future improvements.

When completing the questionnaire, participants are encouraged to answer the question "What do you think about the HaptiFab?" based on their intuition to ensure that the feedback authentically reflects their first impression of HaptiFab. Even if participants are uncertain about some items or if neither adjective perfectly fits, they are required to choose the option that most aligns with their view.

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Table 4. User Experience Questionnaire Scale

	1	2	3	4	5	6	7	
Annoying	○	○	○	○	○	○	○	Enjoyable
Not Understandable	○	○	○	○	○	○	○	Understandable
Creative	○	○	○	○	○	○	○	Dull
Easy to Learn	○	○	○	○	○	○	○	Difficult to Learn
Valuable	○	○	○	○	○	○	○	Inferior
Boring	○	○	○	○	○	○	○	Exciting
Not Interesting	○	○	○	○	○	○	○	Interesting
Unpredictable	○	○	○	○	○	○	○	Predictable
Fast	○	○	○	○	○	○	○	Slow
Inventive	○	○	○	○	○	○	○	Conventional
Obstructive	○	○	○	○	○	○	○	Supportive
Good	○	○	○	○	○	○	○	Bad
Complicated	○	○	○	○	○	○	○	Easy
Unlikable	○	○	○	○	○	○	○	Pleasing
Usual	○	○	○	○	○	○	○	Leading Edge
Unpleasant	○	○	○	○	○	○	○	Pleasant
Secure	○	○	○	○	○	○	○	Not Secure
Motivating	○	○	○	○	○	○	○	Demotivating
Meets Expectations	○	○	○	○	○	○	○	Does Not Meet Expectations
Inefficient	○	○	○	○	○	○	○	Efficient
Clear	○	○	○	○	○	○	○	Confusing
Impractical	○	○	○	○	○	○	○	Practical
Organized	○	○	○	○	○	○	○	Cluttered
Attractive	○	○	○	○	○	○	○	Unattractive
Friendly	○	○	○	○	○	○	○	Unfriendly
Conservative	○	○	○	○	○	○	○	Innovative