TactorBots: A Haptic Design Toolkit for Out-of-lab Exploration of Emotional Robotic Touch

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Figure 1: TactorBots: Haptic design toolkit for exploring emotional robotic touch (a) Hardware modules are worn on the forearm (b) It can be packaged in a compact case (c) It contains hardware modules and a web-based authoring tool

ABSTRACT

Emerging research has demonstrated the viability of emotional communication through haptic technology inspired by interpersonal touch. However, the meaning-making of artificial touch remains ambiguous and contextual. We see this ambiguity caused by robotic touch's "otherness" as an opportunity for exploring alternatives. To empower emotional haptic design in longitudinal out-of-lab exploration, we devise TactorBots, a design toolkit consisting of eight wearable hardware modules for rendering robotic touch gestures controlled by a web-based software application. We deployed TactorBots to thirteen designers and researchers to validate its functionality, characterize its design experience, and analyze what, how, and why alternative perceptions, practices, contexts, and metaphors would emerge in the experiment. We provide suggestions for designing future toolkits and field studies based on our experiences. Reflecting on the findings, we derive design implications for further enhancing the ambiguity and shifting the mindsets to expand the design space.

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CCS CONCEPTS

• **Human-centered computing → Systems and tools for interaction design**; **Haptic devices**; **Empirical studies in HCI**.

KEYWORDS

Haptic Design Toolkit, Wearable, Emotional Robotic Touch, Design Research, Creativity Support, Outside of Lab Study

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1 INTRODUCTION

Touch, the very first sense to develop in the womb [10], is the primary sense for humans to explore the physical world and is integral to our everyday lives. It is also an effective communication channel, as studies have demonstrated that humans can convey emotions solely through touch [25, 26]. These findings have sparked an increased interest in replicating *familiar* social gestures for computer-mediated emotional communication [29]. However, since the meaning-making of artificial touch [56] is contextual and subjective, it is challenging to arrive at a generalizable haptic language [17, 37]. On the other hand, researchers are reconsidering people's willingness to replace interpersonal physical contact [34, 58], and replicating realistic human affective touch with haptic devices may even fall into the uncanny valley [7, 49]. Under this circumstance, we start to ask, what alternatives can we explore?

A recent manifesto proposed by Jewitt et al. highlights the significance of exploring the richness and meaningfulness of social haptics and fostering interdisciplinarity in touch design beyond technology-driven development [34]. Resonating with it, our previous work, EmotiTactor [82], investigated how designers approach emotional haptics, which revealed the emergence of alternative metaphors beyond replicating human behaviors. We tentatively hypothesized that those metaphors could be evoked by robotic touch's *otherness*. *Otherness*, here, is an aesthetic category [8] for describing robot design that exceeds the dominant anthropomorphic or zoomorphic paradigms in their outward form [3], whose inherent ambiguity allows a broader spectrum of possible social responses to robot's behavior which benefits long-term engagement [4, 23, 60]. As extensively discussed in human-robot interaction (HRI), our work plans to intentionally emphasize the *otherness* feature in emotional robotic touch and investigate its impact in depth.

Inspired by the aforementioned findings, we propose treating emotional robotic touch as a "design canvas" that opens up space for alternative opportunities. We aim to expand the design space by better understanding what, how, and why alternative interpretations emerge in the design experience. As ambiguity can be utilized to encourage deeper interaction and more personal relationships when making sense [20], we emphasize the importance of embracing ambiguity in emotional haptic design by leveraging the balance between *the familiarity of interaction - recognizable social gestures* and *the otherness of form - robotic tactor's appearance and texture* [60]. To encourage diverse behaviors, in-situ engagement, and respecting the slowness of reflective, nuanced visceral interpretation, we conducted a longitudinal design exploration outside the lab. The experiment let various background experts dive into the emotional haptic design in an unsupervised condition by giving them the freedom of time, pace, and space.

To empower touch designers in exploring ambiguity-provoked alternatives, a haptic toolkit ready for independent operation in the wild is needed. Guided by a formative study on early prototypes with 12 participants, we developed TactorBots, an open-source design toolkit. It contains 8 plug-and-play wearable modules that render 9 social gestures with servo-driven feedback. Having the design principle of *otherness* in mind, we devise each module in a minimalist form that follows its purpose function [12]. The small-scale modules can be worn on various body parts (Fig. 8c), while we take the forearm as the default due to social acceptability [68]. TactorBots' web-based software allows easy control, modification, and storage of tactile behaviors to support fast prototyping.

For out-of-lab design exploration, we shipped the toolkit to designers, artists, and researchers (N=13) and prompted them to enrich a text-based fictional story with emotional haptics at their own pace. Participants' feedback in the semi-structured interview validated TactorBots' usability and capability as it was accessible, flexible, trustworthy, and expressive. We collected and analyzed the design experience of each participant and uncovered alternative perceptions of surprising robotic gestures, novel practices, and enriched contexts enabled by the flexibility in time and space. While the alternative metaphors were mostly provoked by the intended *otherness* and given narrative, the user's background and self-determined experiment settings also impacted their imagination. Reflecting on our findings, we provide suggestions for designing future haptic toolkits and field experiments. We conclude with design implications to expand the design space extensively by enhancing ambiguity and shifting mindsets.

2 RELATED WORKS

2.1 Interpersonal Emotional Touch

Research in psychology demonstrates the human capability to interpret emotional messages embedded in touch. Foundational psychology research by Hertenstein et al. indicated that beyond the hedonic tone and the intensity of emotions [35], a pair of strangers could convey distinct emotions (i.e., Anger, Fear, Disgust, Love, Gratitude, and Sympathy) to one another solely by touching on their forearm [26]. Their subsequent full-body study showed that Happiness and Sadness could also be decoded [25]. Later studies by Thompon et al. suggested that romantic couples can even convey self-focused emotions such as Envy and Pride through direct touch [70]. These studies also identified the commonly used touch gestures when communicating each emotion based on visual observation [25, 26, 70]. Recent works demonstrate measuring and quantifying emotional touch with automated techniques, such as infrared video [24, 46], electromagnetic tracking [24, 46], or depth camera [76], which provided a more precise understanding of emotional interpersonal touch.

2.2 Gesture-based Emotional Haptics

Creating affective touch has become a significant trend and challenge in HCI and HRI. Researchers previously designed expressive agents such as PARO [78], Haptic Creature [1, 61, 77], FlexiBit [11], and Huggable [64], which can provide therapeutic tactile cues or expressive valence and arousal affects. Inspired by interpersonal emotional touch, gesture-based haptic technology has greatly improved the specificity of emotional communication [30, 36, 82], which is also the approach we employed. Table 1 lists the existing gesture-based haptic platforms with various technologies [5, 16, 17, 30, 31, 36–38, 51, 53, 63, 81, 82]. We compared TactorBots with them based on qualities in the first row, which show that TactorBots: (1) could render the largest number of touch types (N = 9); (2) is the first wearable haptic platform that could be used to explore emotional robotic touch on the full body; (3) is the first to be intentionally designed for deploying in the wild.

Among the listed works, platforms that studied emotional haptics were more relevant to us. For instance, 16 participants used vibrotactile TassT to design mediated touch for conveying 8 emotions [30], whose resulting emotion-gesture correlations matched well with earlier psychology research [26]. Following the trend of moving beyond vibrotactile [34], later works explored other modalities. Foo et al. developed an SMA garment [16] and investigated user expectations in using "warm touch" to convey emotions through crowdsourcing online surveys [17]. Kim et al. [37] explored swarm robots to provide social haptic cues and analyzed the robot's behaviors for expressing 6 primary emotions. We previously [81] built

Table 1: A comparison of prior gesture-based social haptics research with TactorBots (Num: number of gestures, Emo: Emotion, Wea: wearable)

Related Works	Technology	Explored Touch Gestures											Emo	Wea	Placement	Out of Lab
		Hit	*Pat*	*Push*	*Rub*	*Shake*	*Squeeze*	*Stroke*	*Tap*	*Tremble*	*Other*	*Num*				
Baumann et al. [5]	Servo						•		•			2	•		Wrist	
Stanley et al. [63]	Servo						•		•		Drag, Twist	4		•	Wrist	
TaSST [30, 31]	Vibration	•			•		•	•	•		Press	6	•	•	Arm	
Tickler [38]	SMA							•			Tickle	2		•	Wrist	
SwarmHaptics [37]	Swarm Robot			•			•	•	•		Hug	5	•		Arm	
Touch me gently [51]	SMA							•	•		Grab	3		•	Arm	
Nunez et al. [53]	Voice coil/DC							•				1		•	Arm	
Foo et al. [16, 17]	SMA						•					1	•	•	Upper body	
KnitDermis [36]	SMA						•	•			Pinch, Twist	4		•	Full body	
EmotiTactor [82]	Servo	•	•	•		•	•		•	•		7	•		Arm	
TactorBots	Servo	•	•	•	•	•	•	•	•	•		9	•	•	Arm/full	Yes

	Research Goal	Wearability & Deployability	Study Setting	Participants	Main Findings
EmotiTactor [82]	Explore how designers approach emotional robotic touch	• **Table-grounded** • Handmade device • Bulky integrated device • Local authoring software	• **Lab study** • Elicitation study with open context • Questionnaires and brief interview in the end	Interaction designers without experiences in haptics (N=11)	• Observations on various strategies, metaphors, and responses • Hypothesis that **alternative metaphors** beyond human touch were provoked by robotic touch's **otherness**
TactorBots	Produce **ambiguity** with **otherness** to understand **what, how, and why alternatives emerge** in designing emotional robotic touch	• **Body-worn** • 3D printing • Small, light-weight, modular devices in a compact case • Web-based software	• **longitudinal out-of-lab study** with flexibility in time and space • **Unsupervised** design task: expressive haptic storytelling • Semi-structured interviews pre and post design task	• Designer and artists (N=4) • Haptics Researchers (N=4) • Researchers in adjacent fields (N=5)	• The designed otherness and longitudinal out-of-lab setting let us uncover what, how, and why **alternatives** in **perceptions, practices**, **contexts**, and **metaphors** emerged • Design implications about **enhancing ambiguity** and **shifting mindsets** to expand the design space

servo-driven interfaces with pre-defined haptic patterns and found the emotional signals were decodable. Later we refined the device and invited 11 designers to create the haptic cues for 8 emotions [82]. While some emotional touch patterns were found, the above research also revealed the interpretation of touch could be contextual and subjective [17, 37]. At the same time, they mentioned people pictured metaphors when designing [17, 37, 82]. Most intriguingly, our past work, EmotiTactor [82], spotlighted alternative metaphors beyond human hand gestures (e.g., shaking cradle for Love). We hypothesized the robotic touch's "*otherness*" evoked such alternatives. Taking EmotiTactor's findings as starting point, we aim to further explore the alternative opportunities of emotional haptics by producing ambiguity with intended *otherness*. Table 1 shows the comparison: while building upon [82], TactorBots toolkit has greatly improved in deployability and wearability, which enabled our design exploration in a longitudinal out-of-lab setting with unsupervised tasks. Our work extensively expands the findings by systematically analyzing the design alternatives in various dimensions fostered by the intended ambiguity and flexible experiment setting. The two design implications derived from our findings aim to push the boundaries of the current design space.

2.3 Prototyping Toolkits for Haptics

Developing toolkits for haptic prototyping is essential, as imaging a haptic cue without direct perception is challenging, and building a haptic device from scratch requires specialized engineering skills. GUI often supports the design and sense-making process. As the conventional modality, the graphical authoring tools for designing sensations with single or arrays of vibration motors are maturing [54, 59, 61]. However, toolkits for exploring other modalities, such as force feedback or kinesthetic haptics, usually need custom hardware. Many prior works attempted to provide approachable solutions with low-cost open-hardware features. Hapkit [50] and Haply [13] are educational tools for exploring force-feedback sensations, which have greatly expanded the community and supported the haptic theory learning. WoodenHaptics [18] made spatial haptic interfaces accessible. Another key motivation for haptic toolkits is providing flexibility in designing various sensations for different body placements. Compressables [15] supported the open-ended design with compression-based (pneumatic) haptic interactions across all sites of the body. TactJam [74] enabled the collaborative design of on-body vibrotactile feedback. ANISMA [48] could render different touch gestures with SMA-based skin deformation devices. Beyond designing haptic cues for specific use cases, soma design [27] toolkits also help raise body awareness. For instance, Soma Bits [73] and Menarche Bits [62] are introduced to support the process of engaging bodily sensory experiences with subtle or uncomfortable tactile stimulations to cultivate somaesthetic appreciation and open a design space of intimate body-worn technology. While there is no existing haptic toolkit that renders robotic social gestures for designing emotional robotic touch, we are inspired by the qualities collected from the above literature and aim to make a haptic toolkit that has approachable custom hardware controlled by a web-based GUI, which can provide versatility in touch design and support the reflective and thoughtful interpretation on bodily experiences to foster alternative understandings.

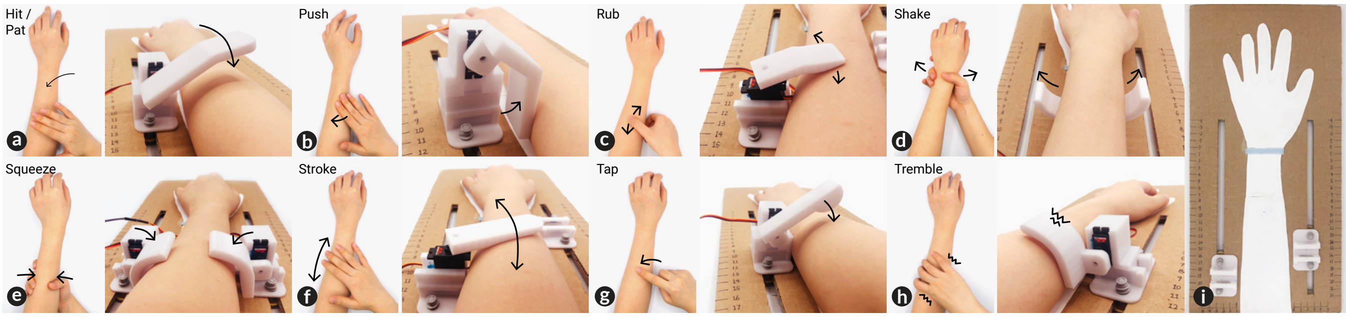


Figure 2: (a-h) Design of Tactor Modules (right side) that perform each social touch gesture (left side); (i) Testing interface with sliders and rails

3 DESIGN OF TACTORBOTS

TactorBots is a design toolkit for exploring emotional robotic touch outside the lab. We followed the principles of designing toolkits for wearable embodiment interaction summarized by Ledo et al. [39] and Lei et al. [40] and set our design goals as Accessibility, Flexibility, and Trust. Moreover, we regard our toolkit as a probe for supporting evocative tasks and eliciting inspirational responses [19]. To provoke alternative interpretations, another key design goal is producing ambiguity by leveraging the *familiarity* and *otherness* of the robotic touch. Specifically, we make robotic interfaces perform distinguishable gestures while remaining true to their mechanistic nature in appearance and texture. This section presents the design process, features, and user flow of TactorBots platform.

3.1 Early Prototypes and Formative Study

We started by investigating the features of robotic touch gestures. We built robotic tactors (Fig. 2) for performing target social gestures (Appendix A Table 3) inspired by the servo-driven interface we previously designed for EmotiTactor [82]. While past work fixed the Tactors' locations on an integrated device with no specific reason [82], we propose studying the perception and placement of robotic gestures to inform the toolkit design. The table-grounded prototypes were designed in 1 DoF, driven by a micro servo (AGFrc B11DLS), as they are low-cost and easy to control precisely. To preserve the *otherness* feature, we designed tactor prototypes in a simple minimalist form that was shaped purely based on their purpose functions and fabricated by 3D printing. We defined sample parameter settings on motion, rhythm, and intensity for each gesture (Appendix A: Fig. 11) and conducted an identification study. We also developed a testing interface (Fig. 2i) that included rails and sliders to explore each tactor's appropriate placement. A formative lab study with 12 participants (Appendix A) indicated that our 1 DoF Tactor prototype for each gesture could be recognized well, with an overall accuracy of 83.4% (Fig. 13). As participants were confused between Pat and Tap (33%, Fig. 13), we later extensively modified the Tap Tactor design in TactorBots. In the placement investigation, we found many overlaps in contact range preferences (Table 4), revealing that integrating all Tactors in a single device with fixed position and order may be challenging. Moreover, the table-grounded device restricted arm movement, leading to numbness and fatigue. Therefore, we designed our final TactorBots in a wearable modular form factor to allow flexible body placement and limb movement. Modularity also enables a partial on-demand combination of gestures for different applications.

3.2 TactorBots Hardware Modules

According to the formative study, we designed the TactorBots hardware with wearable modules (Fig. 3). Most Tactors are built upon the early prototypes (Section 3.1), except Stroke and Rub, as their large lateral moving range cannot fit into the new form factor. Each small-scale (8 x 5 x 4.5 cm), lightweight (72 g), and low-cost (< $15 per Module) wearable module comprises three main parts: Case, Cover, and Tactor. In Figure 3, we take the Shake Module as an

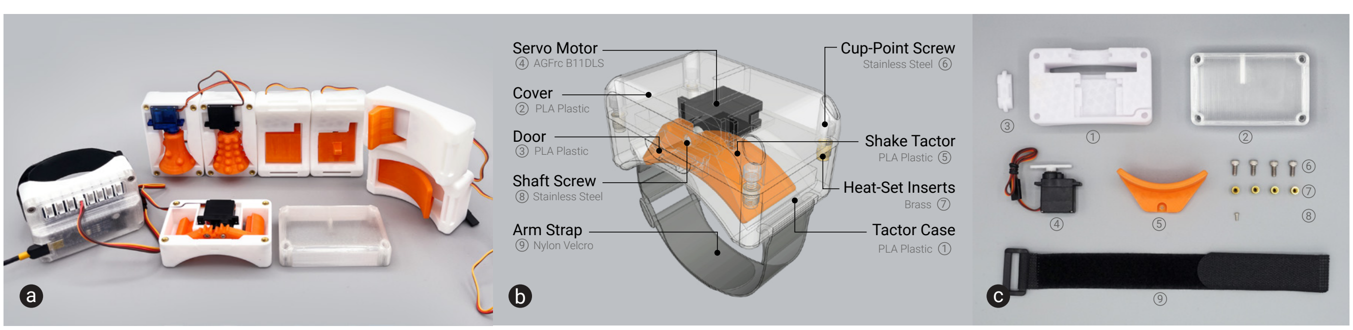


Figure 3: (a) TactorBots hardware modules (b) Mechanism of Shake Tactor (c) Components to make a Shake Tactor

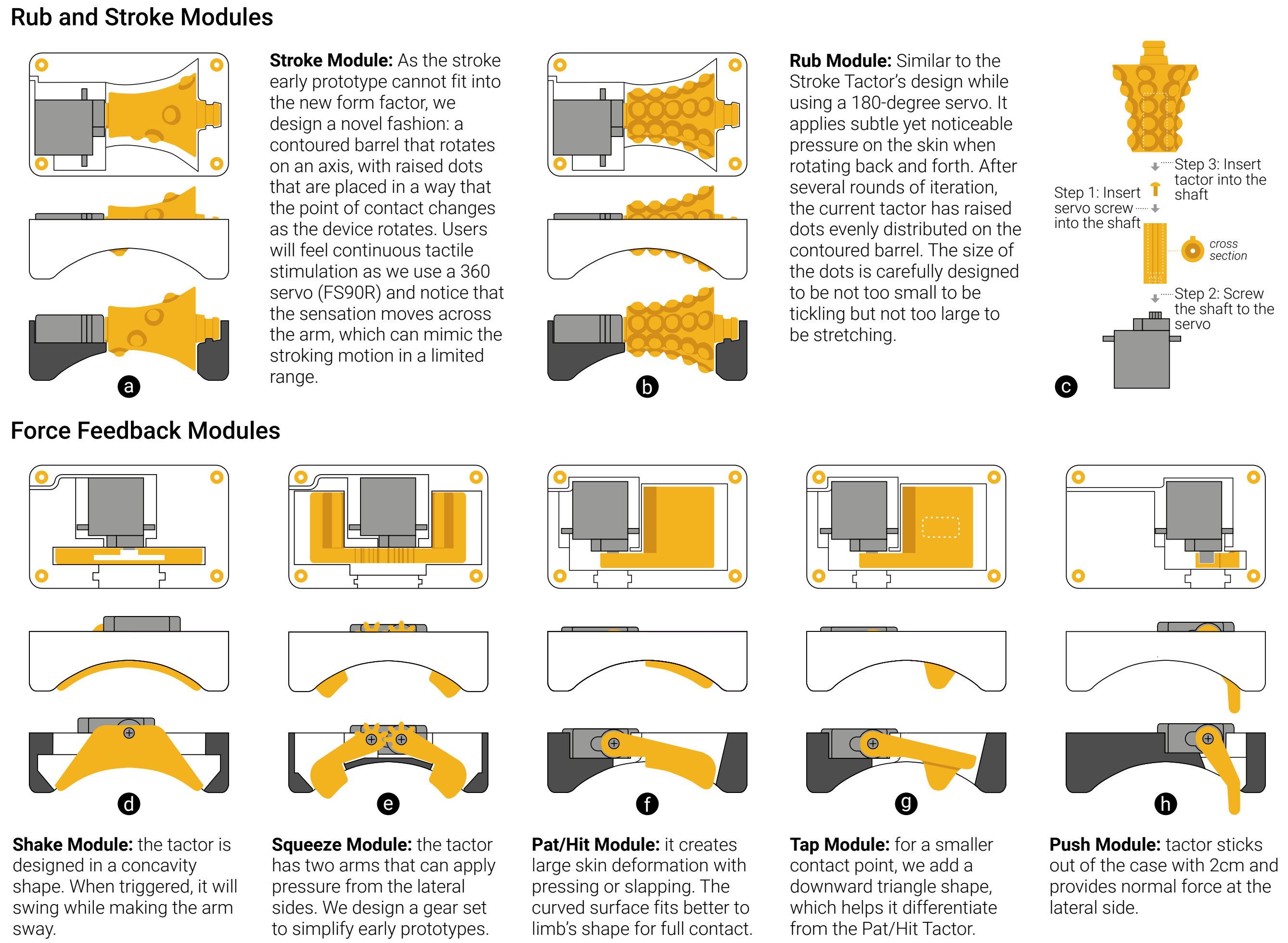


Figure 4: Design of the Tactor Modules

example. The internal Tactor's shape and mechanism (Fig. 3b(5)) are designed to perform the target gesture in a minimalist form. The Tactors are driven by AGFrc B11DLS micro servo (180 degrees, 2.8 kg-cm) except Stroke Tactor, which uses an FS90R continuous rotation servo (360 degrees, 1.5 kg-com). While having a consistent enclosure, each case and cover are adaptively designed to allow the Tactor's smooth movement while fixing the servo's placement. We restricted the Tactors' motion range in the software to prevent overrotation for safety. An open entrance and small door (Fig. 3b(3)) are designed for assembling Tactor to the servo shaft easily. The enclosure and Tactor's outer edges are filleted for comfort and the downward surface fits the general-size limb shape with an attached adjustable velcro strap. The modules are designed using Fusion 360 and printed in PLA plastic. We make the cover clear while giving the Tactor a distinct orange to make the mechanisms visible, which supports sense-making. We open source[1] all the main parts in STL format with suggested printing settings and provide the hardware and accessories information in the Bill of Materials form (BOM).

[1]https://www.ranzhourobot.com/tactorbots/

TactorBots also contains a Home Module hosting a custom control board, which bridges the Tactor Modules and PC. Tactor Modules are attached to Home Module with JST connectors, which are stable when plugged in and appropriate for wearable haptic applications with large-range body movements. Figure 4 presents the design of each Tactor Module. In our pre-assembled kits for following design exploration, we also provide the extension strap for fixing the Modules on different body parts and a pry tool to support unplugging the JST connectors.

3.3 User Flow and TactorBots Software

To operate TactorBots, the designer first opens the TactorBots web-based authoring tool in Google Chrome and attaches the Home Module to the PC with a micro USB cable (Fig. 5 Step 1). They then follow the instructions in the ***Connection*** (Fig. 5d) tab to connect it through Web Serial (Step 2). The next step is to proceed to the ***Tactor Information*** tab (Fig. 5b), which depicts the form factor, the recommended placement based on our formative study, and potentially associated emotions according to our prior research [82]. When the designer decides to use a specific Tactor, they click

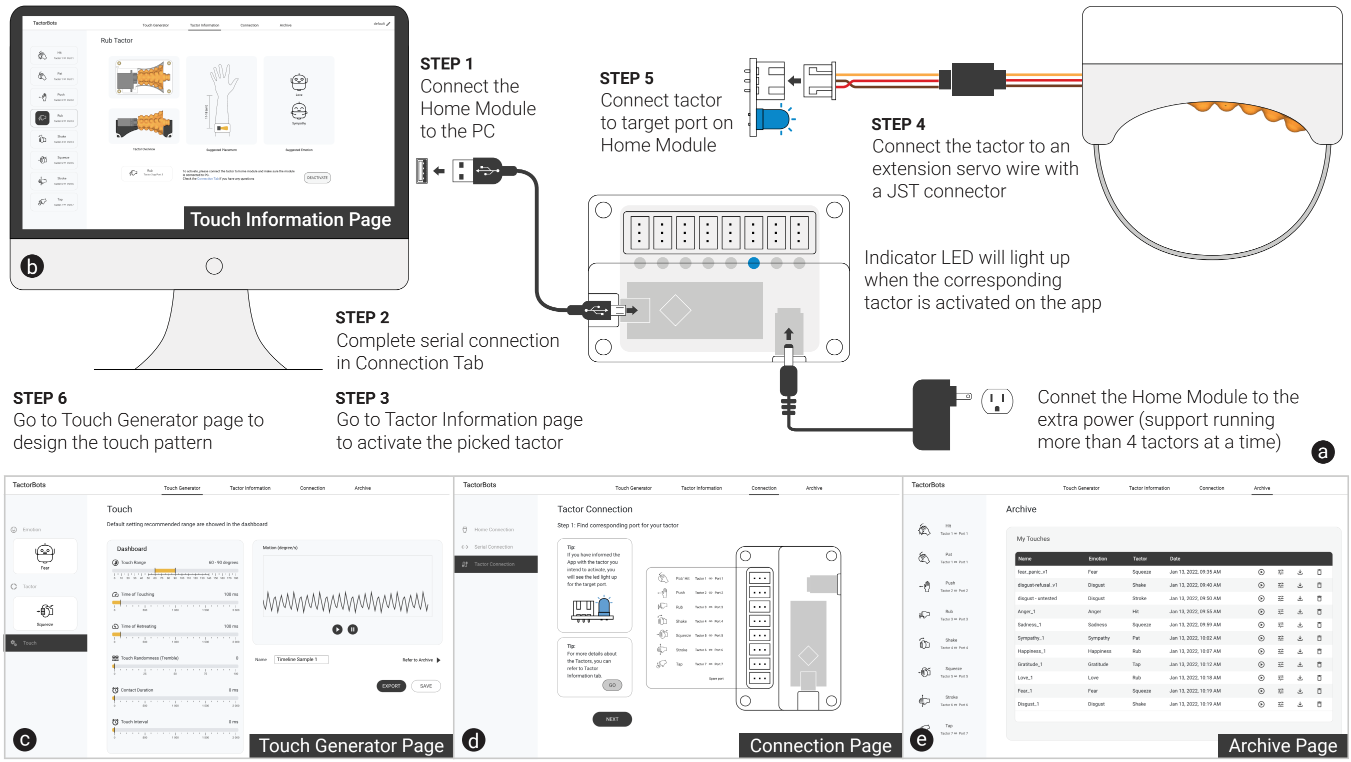


Figure 5: (a) User flow of operating TactorBots Toolkit. Main tabs on GUI authoring tool: (b) Touch information (c) Touch generator (d) Connection (e) Archive

the Activate button. An LED on the Home Module will light up to indicate the corresponding port. After attaching the Tactor to the port using a servo wire with a JST connector, the user can wear the Module and proceed to the ***Touch Generator*** (Fig. 5c) to design the haptic cues. In this tab, six sliders control the Tactor behavior. For instance, the designer can set a minimum and maximum angle in *Touch Range* (Fig. 14a) and then use *Time of Touching* (Fig. 14b) to control how long the Tactor moves from the maximum to the minimum range. See Appendix B for more details about the parameters. When satisfied, they can name the pattern and save it to the ***Archive*** (Fig. 5e), where stored patterns can be played back and exported. The users' information and design data are stored in our backend for research analysis.

4 DESIGN EXPLORATION OUTSIDE OF LAB

We conducted a longitudinal out-of-lab design exploration to probe the design space of emotional haptics and characterize TactorBots' design experience. We shipped the toolkits to 13 participants with diverse expertise (Table 2). Our study focused on collecting participants' design experience to gain insights into potential overlaps and differences in their practices *(what)*, inquire about their design process and strategy in detail *(how)*, and analyze the reasoning behind design decisions *(why)*. We were particularly interested in the the alternative perceptions, practices, contexts, and metaphors.

4.1 Study Procedure

4.1.1 Pre-task Interview. When a participant received the TactorBots package (Fig. 6), we scheduled the pre-task interview. This semi-structured interview (lasting 30 mins) was held on Zoom to introduce our design exploration and learn about the participant's area of research or design practice and prior experiences in related topics, aiming to investigate how their background could impact their design experiences. We defined the related experiences in Table 2 as follows: *Haptics Design (HD)* - general research or design with haptics; *Social Haptics Design (SHD)* - haptic design for social interaction; *Emotional Haptics Design (EHD)* - design haptic cues that can express distinct emotions (e.g., Fear, Happiness). Participants' names and representative works [2, 14, 22, 32, 42, 43, 45, 52, 67, 69, 75, 79, 80] are also listed in Table 2 to show their expertise.

4.1.2 Design Task: Expressive Haptic Storytelling. Following the interview, we sent out an email that included TactorBots' *web-based instruction* (step-by-step tutorials with video demos and text descriptions), a link to the *expressive haptic storytelling design task*, and an *shared online folder* to store design notes and photo/video documentation if they were willing. As for design tasks, prior studies have explored different approaches. For instance, giving open context for eliciting participant's intuitive behaviors with little bias [37, 82] or prompts that defined the touch sender or receiver as another person [30], friend [17], or partner [46]. Our goal was to provide participants with first-hand experiences of perceiving and

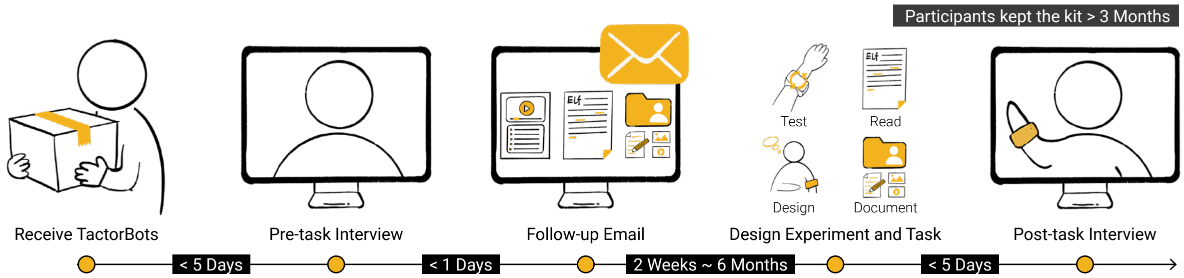


Figure 6: Study Procedure of the design exploration outside of lab

designing emotional haptics for creative interpretations. Thus, we devised a specific context for engaging exploration, demonstrating one of the typical use cases of emotional haptics - expressive haptic storytelling [33]. The fictional text-based story for the design task had two main protagonists: a game player (receiver) and an elf (toucher). We used "elf" because it was an abstract and ambiguous concept compared to an existing being or object. The narrative's plots were created based on the 8 emotions (i.e., Fear, Disgust, Anger, Sadness, Sympathy, Happiness, Gratitude, and Love) that were proven to be communicable in interpersonal touch [25, 26]. Within the story, some highlighted blocks informed an expressive haptic cue needed to be designed. The participant needed to learn to use TactorBots, design, and save the haptic cues according to the guidance for completing the task at their own pace. More details about the narrative content can be found in Appendix C.

4.1.3 Post-task Interview. When completing the design task, we asked the participant to notify us instantly to schedule the post-study interview (scheduled within 5 days, lasting 90 mins). So they could remember the experiment details. In the semi-structured Zoom interview, we first collected feedback on our Toolkit design. We then learned about their design experiences with robotic touch perception, schedule and space they chose to take the experiment, strategies for designing the touch, and the design metaphors they pictured. We discussed and prompted them to reflect on the reasoning behind the design decision. As a generative discussion [71], we also collected novel inquiries emerging in the conversations.

5 RESULTS AND FINDINGS

We invited 13 participants, who were divided into 3 groups according to their expertise (See Table 2) and distributed in 6 states of the US. They were recruited by referral, beginning with our own networks and referrals of early recruits. 8 of the participants had prior experience in haptic design. Among them, 7 also previously explored social haptics, while only P3 and P7 specifically worked with emotional haptics. Notably, P7 [44] and P9 [14] were aware of psychological findings on existing patterns in interpersonal emotional touch [25, 26]. All interview sessions were video recorded and transcribed into text-based documents. We categorized the data based on the leading questions or topics and employed thematic analysis to identify recurring themes within the data. We curate the study findings in Table 2, which includes each participant's background, experiment schedule, main metaphors, and highlight points in their design experience. In this section, we validate the usability and capability of the toolkit design, discuss the themes emerging in the experiment, and uncover the patterns between experiment strategies and design decisions.

5.1 Feedback on Toolkit Design

Participants enjoyed the usability of TactorBots. They believed "*the plug-and-play feature of the toolkit was simple to operate*" (P7, P11), the software was "*beautiful*" (P8) and "*easy to understand*" (P2), and the user flow was "*slick and intuitive*" (P1). P8 specifically appreciated the design of the indicator LEDs as it smoothed the hardware/software connection process. Following the instructions took a novice (no experience in haptics) designer about 20 mins to learn to use the platform. In comparison, a professional haptics researcher needed only 5 mins. They were impressed by the flexibility of tactors and authoring parameters, as "*it was fun to have this playground of different things to choose from*" (P7). All Tactors were perceived as valuable, which supported different design needs. While explicitly emphasized by P4 and P10, we noticed 12 out of 13 participants chose distinctive Tactors for different emotions (Table 5), with at most two Tactors (mainly Rub and Squeeze) repeatedly used. P10 said: "*When designing Sympathy with Pat, I felt it could also convey Love, which confused me as I wanted to design discernible cues.*" In the end, she found Rub could do an even better job of expressing Love. The versatility provided by TactorBots eased the process of trying out and feeling around the nuanced relationship between touch and emotion, enabling designers to navigate this nuance by iterating and landing a confident design.

Free exploration of bodily placement was fostered by modular wearable fashion. Although many previous studies' default placement was the dorsal side of the forearm [30, 82], P1 and P8 mentioned the ventral side could be more appropriate for intimate emotions, similar to the exposure of a cat's belly. P2 explored placing the tactors on the palm, hand, shoulder, and neck, while P13 tried the entire body and even fixed them to the ankle (Fig. 8c). Wearing TactorBots beyond socially acceptable body parts [68] showed their trust. Many participants mentioned that "*the touches rendered by TactorBots were intimate*" (P1, P6, P11), but no one felt unacceptable or creepy. We found the otherness, legibility, and controllability of TactorBots contributed to trust building. P2 commented, "*the robot's aesthetic quality and transparent enclosure helped me to build trust.*" P1 said: "*the structure of the tactor was easy to understand, and I knew I could have full control of their behaviors, which encouraged me to go wild in the experiment.*" The exposure of the robot's internal mechanism is an essential factor, which was also suggested in HRI design: "*uncovering the hidden thinking process underneath the social robot's skin may increase the robot's perceived honesty*" [28].

5.2 Perception and Interpretation of TactorBots

5.2.1 Novelty and Expressiveness. The sensations created by TactorBots were novel, especially to non-haptic experts. They commented: "*It was magical to feel the tactor moving for the first time*" (P1); "*I had never felt anything like that on my body before*" (P10). More specifically, it was challenging for them to imagine the stimulation before perceiving it. In contrast, haptic researchers (P6, P8) could predict the feeling based on the tactor's shape and structure, while P6 also emphasized, "*I was more interested in the rub and stroke tactor because their spiral mechanism was new to me.*" Participants explicitly pointed out the expressiveness of the Tactors: "*I was just surprised how it provided these emotions that I didn't think were possible*" (P13), while P6 and P11 particularly liked the Touch Randomness parameter as it "*created a sense of liveliness*" (P6).

5.2.2 Interpretation of Robotic Gestures. There were two types of interpretations of rendered gestures: (1) Believed the Tactor Modules "*can indeed perform the gestures as the name suggests*" (P11). These participants utilized the touch gesture concept when designing the emotional cues. (2) Focused on the raw perception and purely regarded the modules as different touch types rather than hand gestures. For instance, P5 suggested: "*I did not very focus on the 'gesture' concepts of the tactors. Instead, I pay more attention to what the sensation itself feels like.*" Most participants had both types of gesture interpretations emerge in the experiment, depending on the tactor behavior and the context. Those results validate that TactorBots rendered gestures were effective and distinguishable while leaving space for personal interpretations and creative associations.

Rub Module. Many participants particularly liked the sensations rendered by Rub Tactor. P3 said: "*Rub was unique.*" P9 claimed: "*Interestingly, I could feel some very gentle or even lively motions by adjusting the parameters (with Rub). Very accidental and surprising.*" Alternative interpretations were provoked by its stimulation. For instance, P3 used Rub to design Disgust because she felt it could provide "*goosebumps*" feelings. P1 mentioned the raised dots on Rub Tactor reminded him of spines on a cat's tongue (Fig. 7a), so he tried to use it to mimic a cat's licking when designing Love. Moreover, P6 felt Rub Tactor's fashion was inspiring, which could even render tingling, tickling, or ants crawling (those sensations were investigated in her own research [42]) by carefully modifying the raised shape or arrangement (Fig. 7b and c).

Figure 7: Inspirations when perceiving Rub (a) P1 was reminded of spines on cat's tongue; (b) P6 suggested modifying dot's arrangement or (c) tip shape to explore novel sensations

Stroke Module. In prior research [24], Stroke usually associates with low-arousal emotions such as Love and Sympathy. In our case, however, it was used for creating high-arousal emotions like Happiness or even Disgust. P11 and P13 supposed it would be a gentle, smooth sensation, but it actually felt "*very wild.*" Other participants commented that the tactor "*could not rotate slower*" (P10), and the cues "*did not match the Stroke in my imagination*" (P3). The potential explanation was that the Stroke Tactor used a low torque continuous servo which could not conquer the friction of the skin and drive the tactor at a lower speed. While differing from our design intention, participants connected this novel and wild cutaneous sensations with various metaphors or concepts like "*goose bumping,*" "*tickling,*" "*crawling,*" "*humming,*" "*crying,*" or "*tapping slightly and briskly.*"

Force-feedback Modules. Participants were generally satisfied with other tactors that mainly provided force feedback. P2 and P3 said they particularly liked the Squeeze Tactor and felt it could communicate many emotions. P7 and P13 said Tap Tactor gave them a pleasant surprise. "*I thought it would be a very harsh and spiky touch as it looks like a knife, but it actually felt very good and relaxing*" (P13). Due to the wearable modular form, the sensation performed by the Push Tactor was reported to be more like "*Press.*" When they set a larger touch range, the velcro strap's tension would also provide tactile constraint, so the entire Module provided "*Squeeze*" or "*Grab*" feelings.

Alternative perceptions of surprising robotic gestures
Participants were more engaged in the Tactors that surprised them, for instance, when perceiving a touch sensation that differed from their imagined capability. This element of surprise was heightened by the intentionally designed *otherness.* While every Tactor has a descriptive gesture name, these were intended as hints or suggestions rather than strict definitions. When the imagined gesture concept and the haptic sensation were not precisely matched, participants relied more on the latter and invoked personal touch descriptions. It could instigate their curiosity to consciously make meaning of the touch, which fostered more creative and reflective interpretations.

5.3 Flexibility in Experiment Schedule

Experiment Schedule Types. Table 2 (column 2) illustrates various processes participants employed. *Design Durations* on the top right corner are calculated through saved patterns' timestamps, which show the time spent on the design task. From the results, we identified 3 typical schedules (S1-3) and two unique cases (S4-5).

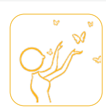
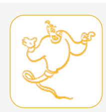
(S1) Went directly to the design task without a priming process (N=4). P6 and P8 explained they could predict most of the perceptions based on Tactor shape due to their haptics expertise.

(S2) Started their experiment by testing all the tactors to learn their capabilities, then read the scenario and designed the touch. They finished all the steps in one day (N =4).

(S3) Learned and tested all the tactors in one day, then took the other days to read the narrative and complete the task (N=3).

(S4) Instead of learning the sensations, P2 first spent the morning reading and immersing herself in the scenario to imagine what tactile feelings could match each emotional context. For instance,

Table 2: The results of exploration process, main metaphors, and design decisions

Group	ID	Participant Background	HD SHD EHD	Work	Experiment Schedule	Main Metaphors		Highlights
Designer and Artist	P1	**Yuguang Zhang** Media art, performance art	○ ○ ○	[79]	S3, 35 min; test, read, design; D1, D2	M4 Imagine the elf similar to a lizard with tail wrapped on arm; M3 Cat licking for love		• The lizard-like metaphor definitely had a expressive tail • Rub tactor's raised dots <> spines on cat's taugh • Explored placement freely
Designer and Artist	P2	**Yutong Xie** Multimedia design, film producing	○ ○ ○	[75]	S4, 30 min; D1	M2 Bodily responses, such as chocking feeling for fear; Light rhythmic tapping as if singing or humming for happiness		• Unique experiment schedule • Did the experiment at home while interacting with her partner and dog • Explored different tactor placement (she and partner)
Designer and Artist	P3	**Hayeon Hwang** Interactive installations in natural history museum	● ● ●	[32]	S2, 40 min; D1	M2 Externalization of human's interoceptions. eg: fast heartbeat for fear, goose bump for disgust		• Regarded the robot as a part of her body rather than external device • Goose bump metaphor (rub) • Made decisions purely on tactor sensation not "gesture name"
Designer and Artist	P4	**Jungu Guo** Interactive installations in science museum	○ ○ ○	[22]	S1, 65 min; D1	M2 Bodily responses and body behaviorr. e.g., throwing up, churning stomach for disgust; biting for anger		• Started with "random" tactors and tweaking parameters freely • Exploring different cues until one moment it evoked the emotion and some metaphors emerged
Haptics Researcher	P5	**Yujie Tao** Haptics, illusions, well-being	● ● ○	[69]	S3, 20 + 15 min; D1, D2, D3	M4 A cartoonish blue ball with short limbs floating in the air. Its body language was translated to tactile pattern		• Unique metaphor that did not provide any direct touch (float in air) • Did not focus on gesture concept of the tactors • Excluded replicating human touch
Haptics Researcher	P6	**Jasmine Lu** Haptics, symbiotic human-device relationship	● ● ○	[42]	S1, 45 min; D1	M4 Fictional inanimate object: ancient armor with a wizard fortune inside; M3 Cat's purr		• Redesigned early emotion when encountering a better sensation • Had cat in room during the experiment, which became inspiration • Rub Tactor modification ideas
Haptics Researcher	P7	**Alex Mazursky** Haptics, novel actuator	● ● ●	[45]	S2, 50 min; D1	M4 Shakily scared like coward "Courage" dog; M1 Rock a baby for sympathy Grandma squeezed my cheek for love		• Had knowledge of interpersonal emotional touch pattern, designed with typical associated gestures while using alternative metaphors
Haptics Researcher	P8	**Romain Nith** Haptics, portable wearable device	● ○ ○	[52]	S1, 40 min; D1	M2 Fast heartbeat for fear, agitated jump for happiness; M1 Pat on shoulder for sympathy		• Could predict most of the touch • Tried to use hand to mimic tactor shape or objects in similar shape to simulate the touch for faster testing
Researchers in Adjacent Fields	P9	**Youngwook Do** Cybersecurity, tangible interaction	● ● ○	[14]	S2, 40 min; D1	M1 Natural human interaction such as holding a person or pillow when watching horror movies for fear		• Was aware of interpersonal emotional touch, followed design suggestions • Had accidental findings when not satisfied with intented tactor (rub for happiness, tried it out of curiosity)
Researchers in Adjacent Fields	P10	**Ruojia Sun** HRI, well-being, textile, wearable	● ● ○	[67]	S3, 15 + 55 min; D1, D2, D3	M1 Tremble and shake when feeling afraid; feel Stroke tactor ticklish, crawling so used for disgust		• Did tried touching herself with hand to test intensity and frequency • Only comfortable with designing touch for herself rather than others • Emphasized consent and agency
Researchers in Adjacent Fields	P11	**Yiran Zhao** Neurophysiology, mental health	● ● ○	[80]	S1, 20 + 30 + 25 min; D1, D2, D3	M4 An abstract creature try to slip on the arm for disgust, dancing butterflies for happiness; M1 Handshake for gratitude		• Relied on the names of the tactors • Hard to keep using one metaphor for all emotions • Abstract elf metaphor with no visual scene, while its behaviors was vivid
Researchers in Adjacent Fields	P12	**Xuanyu Fang** VR, Psychology, emotion regulation	○ ○ ○	[43]	S2, 55 min; D1	M4 A spirit without rigid physical form like Genie in Aladdin; M3 Cat's kneading for sadness		• Did follow the plot and even the development of the narrative • pointed out the gender and scale of elf matter • Cat's kneading metaphor
Researchers in Adjacent Fields	P13	**Patricia Alves-Oliveira** HRI, participatory design for health	○ ○ ○	[2]	S5, 35 min; metaphor elicitation; D1	M5 Similar touch she previous received associated with tactor cues. Feather for Rub; M4 Disney characters; M3 Barking dog for anger		• Metaphor Elicitation: figuring out associated metaphors for each tactor cue to understand and memorize it. • Explored different placement • Used % to measure emotion in touch

HD SHD EHD Work | Saved drafts | Design duration | M1 Interpersonal touch | M2 Bodily response | M3 Animal | M4 Cartoonish charactor | M5 Associated concepts

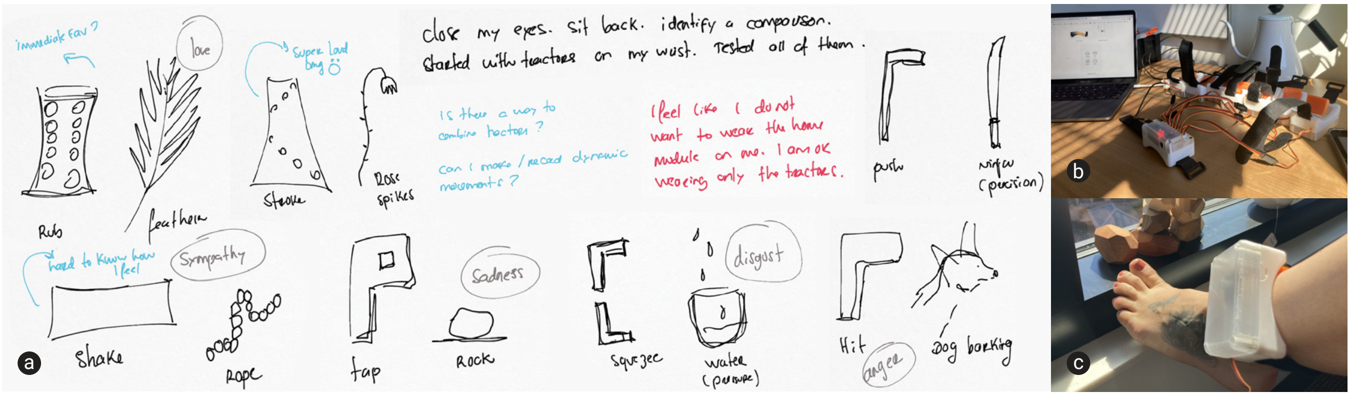


Figure 8: P13 started her experiment with metaphor elicitation. (a) Sketch of the metaphors she imagined when perceiving the touch from each Tactor Module (b) P13 did the exploration in her private office (c) P13 explored placing the robots on various body parts

Happiness was imagined to be "*light rhythmic tapping on the skin as if singing or humming.*" In the afternoon, she tried to tactilize her imagination by using the Stroke Tactor's spinning dots to recreate the slight tap.

(S5) Also started with experiencing sensations without reading the narrative, P13 brought the meaning-making process forward with the practice of "*metaphor elicitation*" (See Fig. 8a). "*I first wanted to discover the personality of each tactor. When I tested them, I thought the touch was too abstract to remember. So I decided to draw comparisons with metaphors on things that would remind me of the tactor when I do the experiment. I put the tactors on my body, closed my eyes, and tried to think what is the most similar sensation I had to this type of touch.*" When asked about how she set the parameters in this exploration, she said: "*I went to random parameters and changed things around while I was perceiving it. Sometimes I would get touches that were really different from the initial feelings, so I would try to explore the limits of that tactor. If some tactors felt more interesting, I would explore them on other parts of the body, such as the neck, shoulder, and ankle.*" (see Fig. 8c)

P13 explained that finding metaphors could be straightforward for some tactors, such as Rub and Stroke. She associated Rub with "*feathers*" because the sensation was soft. Stroke was surprisingly wild and reminded her of the "*spikes of rose.*" She set the "*rock*" metaphor to Tap as it felt firm and heavy and the "*knife*" to Push due to its precision. She supposed Pat Tactor would be a shy touch, but the parameter started with fast speed and rendered a "*dog barking*" like Hit. Shake, however, was hard for her to find a comparison. She felt the movement was very contained, which reminded her of the "*tension of the rope.*" A similar "*contained*" Tactor, Squeeze, was associated with "*water trapped in a tank*" or "*butterfly trapped in a cocoon.*" However, during our conversation, she came up with another metaphor for Shake, "*turtle,*" as the Tactor's concavity shape looked like a turtle's back. Its motion was similar to the tottering turtle walk. P13 believed those metaphors helped her to memorize the features of each tactor and greatly supported her decision-making in the design task. Though she had no experience in haptics, P13 previously explored metaphor-generating methods [41] for speculative design in HRI [3], which could inspire her unique design practice.

Touch Design Strategies. Most of our participants made the design decisions by picking one or two tactor candidates for each emotion and spent more time tweaking the parameter settings. As the only participant who had no experience in haptic design but chose S1, P4 used "*randomized selection*" strategy in the design as he was exploring random sensations with various tactors until finding a cue that could evoke him with the target emotion. All of our participants followed the emotion order in the story when designing, while there were some exceptions. P7, for instance said: "*When I was designing fear with squeeze, I found happiness or excitement along the way. So I picked the same tactor for both of them but set them with different parameters.*" P6 and P9 also mentioned having the experience of going back to the early emotion and redesigned it when encountering a more appropriate touch sensation in later exploration. 8 participants utilized the Archive to save draft patterns, while only 1 haptics expert did so (pencil icon in Table 2). P1 and P6 particularly appreciated this function as the differences between touch were subtle so they would save several drafts and make the final decisions after comparing different cues or creating a new pattern built upon a stored version.

Alternative practices in experimenting followed intuition
Without strict protocols, many participants split their experiment into multiple days, and some employed unique practices. Before starting touch design, one elicited metaphors based only on perceived sensation, and another had concrete tactile imagination according to the text-based story. Participants showed great patience in sensing the nuances signals by comparing draft patterns or exploring various placements. Those alternative practices were fostered by the longitudinal setting and the freedom of time and pace granted to participants. When studying with expert designers and researchers, respecting their intuition and letting them be themselves could maximize their potential. Learning their techniques also informs future exploration with novice users.

Figure 9: TactorBots outside of the lab. (a) P11 brought TactorBots to Los Angeles and did the task during the trip. They said, "the bots are enjoying California sunshine" (b) P7 kept TactorBots on his desk in the research lab (c) P12 placed the Toolkit on the windowsill and stayed with his painting materials (d,e) P2's dog and P3's cat were attracted by the robots during the in-home experiment. They also became inspirations for touch design.

5.4 Flexibility in Space

As part of the out-of-lab design exploration, our participants chose their design environment themselves (see Fig. 9). The Modules' robustness and the kit's compactness (Fig. 1b) enable such deployability. Most of our participants took the study in a private space, such as home or private office, where they could immerse themselves in the experiment without distractions. Many participants tried different body placements of TactorBots. An environment they were familiar with could provide a trustworthy space for exploring the body's boundaries (Fig. 8b and c). Another interesting by-product of the at-home study was the interaction with family members. P2, for example, invited her partner to join the study. She tested the designed touch patterns on his body and realized "*fixing the tactor on the neck was not a good idea.*" The pomeranian dog (Fig. 9d) in P2's home was curious about the system and would always pay attention to the robot when it was running. Similarly, P6's cat (Fig. 9e) kept staring at the bots, attracted by their strange sound. Although they did not try putting the Tactors on the pets due to the concern of pulling hair, interactions with the pets became their inspirations in the design: the sensations of a cat's purr or brushing a pomeranian's hair bonded to the Love feeling.

Beyond the active interaction for design tasks, the long-term study also created a space for passive interaction, as the kit would stay with participants for at least 3 months. P11 decided to take the design task during a trip to Los Angeles and took the kit with them. When they arrived, they placed the modules on the windowsill and shared the photo (Fig. 9a) with the caption: "*the bots are enjoying California sunshine.*" P7 kept the Tactorbots on his desk in the research lab, where he built and tested novel haptic devices every day (Fig. 9b). P12 left the kit at home and put it in the corner with a bunch of painting materials (Fig. 9c). Although we did not have weekly check-in activities [71] to investigate the engagement and relationship building on how participants lived with the kit would make changes, some participants mentioned that during the time they kept it, "*I can feel the bots belong to me, and we have bonded at some level*" (P1), which also contributed to the trust building.

Alternative contexts enriched by various environment
Our results uncovered that nuanced factors in the environment (e.g., family members at home) inspired the design decision. The familiar and trustworthy space encouraged more immersive and boundary-pushing design with touch. Those enriched contexts observed in unsupervised out-of-lab settings remind us of the natural tendency of designers to get inspiration from their surroundings, which we usually overlook in traditional studies. The active and passive long-term interaction induced relationship-building between people and artifacts, creating space and time for ideas to flourish and for rethinking our thinking.

5.5 Metaphors and Design Rationales

Main Metaphors. Participants pictured various metaphors to make meaning of the tactile sensations, which were categorized into 5 typical types. We listed and illustrated the main metaphors for each participant in Table 2 column 3.

(M1) Interpersonal touch: Participants recalled or imagined how they touched another person or received the touch when communicating certain emotions. (Set as primary metaphor: 2, Total: 6)

(M2) Human bodily response: Designed the touch by referring to their bodily feelings when they had a certain emotion, such as fast heart rates or goosebumps. (Primary: 4)

(M3) Animal behaviors: (Primary: 0, Total: 4)

(M4) Cartoonish characters: Included original and classical animated characters. (Primary: 7, Total: 8)

(M5) Objects or concepts: Associated concepts elicited from tactile perception. (Primary: 1)

The most employed metaphor was M4, a novel metaphor compared to previous research [17, 82]. While the fictional story inspired it, various approaches were shown. Most M4 participants (P1, P5, P6, P12) pictured one original character and used it to design most of the emotions, similar to playing a movie in their minds. Surprisingly, though P7 knew the prior work in interpersonal emotional touch, his primary metaphor was M4 while picturing different characters from the old cartoons. Similarly, P13 also referred to Disney movies. While picturing M4, some immersed themselves in the narrative and imagined the characters staying around their forearm area, "touching" them, intentionally or unintentionally. But the imagined "elf" usually would not touch with "hands." Instead, they touched with tails (p1) or the entire body (p11). Some (P5, P7, P13) could "translate" the character's body language or typical scene into a tactile pattern. For instance, designing Anger with a build-up of trembling followed by a strong Hit translated from the metaphor of "*steam coming out of ears*" (P7 and P8, Fig. 10). Instead of consciously imagining, M3 mainly emerged in the design process provoked by certain cues or pets in the environment. Unlike simply picturing furry creatures touching you with "paw" [82], our participants tended to associate the cues with typical animal behaviors such as cat's "*licking,*" "*kneading,*" "*purring,*" or dog's "*barking.*" Though we did not provide a fluffy animal-like texture, people could still associate this "other" touch with the pet's features. M5 mainly came up from P13's metaphor elicitation (Fig. 8).

When analyzing the relationship between user background and metaphor, we noticed 3 out of 4 designers and artists used M2 as the primary metaphor. A potential explanation was designers are trained to be more confident in expressing their inner selves to the external world. Intriguingly, none of the haptics researchers utilized M1 as a primary metaphor. P5 and P6 explicitly explained they excluded M1 because they acknowledged the challenges of replicating the realistic human touch with existing technology. When cross-comparing experiment schedules and metaphors, we discover that participants who split their schedules into multiple days were more likely to come up with alternative metaphors beyond human behavior (M1, M2). We hypothesize that those participants perceived the robotic touch in one day and did the task the other day, allowing them more time to digest and process those novel haptic cues. This, in turn, foster more reflective interpretations when designing.

Metaphor's Design Rationales. Based on our in-depth interviews with each participant, we identified design rationales for those metaphors to explain why and how they came out.

Emerging Metaphors for Primary Emotions. Participants reported that the design of most of the emotions was intuitive, especially for some primary emotions (Anger, Fear, Disgust, and Happiness). They could have the metaphors come to their mind immediately without consciously thinking. For instance, when designing Fear, participants usually tried to create a certain rhythm of sensations to mimic trembling and fast heart rate (P3) or the scene of themselves holding (Squeeze) another person or a pillow when watching horror movies (P9, P11). While some participants' primary metaphors were not M1 or M2, they suggested Fear and Anger were too intuitive to connect to human interactions as they indeed used touch to convey them in daily life.

Intentional Metaphors by Imagination and Association. Gratitude as a prosocial emotion was the most challenging to design for most of our participants. It was "*ambiguous*" (P12) and "*abstract*" (P3). Thus, they needed to actively sort out the potential metaphors associated with this emotion in their mind, similar to S4 used by P2. In the end, many thought about the "*zen*" concept, picturing some characters sitting peacefully with folded palms. P3 and P5 used gentle Shake as it could show the "*beauty of balance,*" while most other participants (P8, P12, P13) chose Tap and Pat to simulate "*bowing,*" "*worship,*" or "*kowtow.*"

Provoking Metaphors from Touch Perception. Metaphors could be intentionally imagined based on perception (M5) or emerged unintentionally. Surprisingly, the most commonly used tactor for Disgust was Stroke. No participant thought about using it until they tried the Stroke Tactor. As mentioned in Section 5.2.2, many participants felt when it rotated fast, the "*crawling*" (P10), "*churning and grueling*" (P5) movement was "*wild*" (P11 and P13), and even "*uncomfortable*" (P10), which provoked the metaphor of a sick character that was "*curling and rolling*" (P5). Sometimes when participants picked a tactor and tweaked the parameters for designing one emotion, they would suddenly feel the sensation could express another emotion even better, coming together with a new metaphor.

Why Not Test By Hand Behavior? Only P8 and P10 tried to use their hands to touch their bodies for design. P8, a technical haptic researcher, used his hand because he was impatient to swap different tactors repeatedly. He shaped his hand to mimic the tactor or found objects in similar shapes to simulate the sensations for faster testing. P1 tried to test by hand once but found "*it was too intentional. I would clearly predict the touch, similar to how people don't feel tickling when they tickle themselves.*" Although the tactors were also controlled by himself with intention, the experiences were very different. P11 introduced a mechanosensory phenomenon to support such interpretations. They mentioned: "*there is a finding that if you pat me or if I pat myself, a lot of these neurological responses are the same, but the activated regions in the brain are different [9], which puts robotic devices into an interesting place.*"

Alternative metaphors evoked by otherness and context
While pictured metaphors were mostly beyond human touch, novel metaphors like cartoonish characters, special behaviors of animals, and abstract concepts elicited from robotic sensations also excluded "hand-like behaviors." Designers preferred bodily response metaphors, haptics researchers excluded hand gesture replication, and those who took multi-day experiments were more likely to picture alternative metaphors. The *otherness* of the robotic touch loosens its entanglement with the human hand, leaving space for generating novel metaphors with different rationales. As touch interpretation is context sensitive, the given narrative, participants' background, experiment process, and environment all impacted their imagination.

6 SUGGESTIONS FOR FUTURE EXPLORATION

6.1 Haptic Design Toolkit

Though wearable modular fashion enables flexibility in the placement, switching connectors with JST was tedious. Future work could try magnetic self-mating [6] connectors. P5 and P11 suggested making the Tactors (orange part) themselves swappable within the same wearable Module for convenience. Though the servo noise was unignorable (P1, P5, P13) and could be a distraction, it contributed to some negative or violent emotions, such as Anger, which could be used constructively in certain situations. While participants commented positively on the software functionality, they gave some suggestions. P8 recommended we simplify the parameter names and amount for non-experts, while P7, P10, and P13 hoped to define a more complex touch sequence that contains multiple haptic clips. P9 suggested trying graphic controllers similar to [14]. Those comments informed that customizable authoring methods that meet user expectations, from simplicity for novice users to mastery for experts, will be needed.

Our software provided suggested emotions (SE) and suggested placement (SP) to support the design (Fig. 5b). The participants showed various attitudes towards them. Some followed the suggestions (P7 and P9), while they reflected that they were biased by their prior knowledge of interpersonal emotional touch [25, 26]. Some participants only referred to SE when facing challenges for certain emotions (P11), and some utilized the SE for rethinking (P1) when they noticed surprising associated emotions. Other participants (P2, P3, P13) ignored the suggestions when designing. Although induced some bias, our suggestions were more supportive in inspiring the users rather than manipulating their opinions. While Design Suggestion is valuable for a design tool, P1 suggested putting them into a hidden menu that only appears when demanded.

P10 specifically emphasized "consent" in the discussion as she envisioned implementing the emotional haptics in future everyday life. We supposed there was implied consent when the user agreed to put on the wearable haptic device. However, P10 argued, "*I agree to wear the device does not necessarily mean that I am willing to receive this certain cue at this specific time.*" P13 also suggested, "*An indicator nudge might be helpful before the robot starts to perform the touch.*" Although TactorBots enabled immediate stop in the software or unplugging the device, P10 hoped to have a more intuitive approach, such as "*just by touching the robot.*" While more in-depth investigations on consent for wearable-robot-initiated touch are needed, we noticed a preference for negotiating the agency within haptic channels.

6.2 Longitudinal Out-of-lab Study

Our longitudinal out-of-lab setting greatly enriched the design experience but granting too much freedom did not work for everyone. While most participants completed the design experiment (Fig. 6) within three months, 3 took about six months. In the post-study interview, they suggested that some form of reminders or schedules would be helpful to keep them on track, as too much freedom made them prioritize finishing our task less when they had a busy life.

Debugging hardware devices was challenging in the remote study. Our platform was generally robust, but the users had to follow our instructions to connect the Tactors with the Home Module using JST extension wires, or it would short circuit and burn the Arduino. 2 Participants had such problems and we had to exchange their kit. Participants who "broke" the hardware became hesitant to use them after receiving the new kit. Thus, we needed to give them more confidence by being patient and responsive or even guiding them through the user flow. Future hardware needs to be more error-proof in design but also to guarantee the users are clear about the instructions, especially for more experienced users, as they are more likely to overlook some detailed rules.

Our archive system only stored the touch patterns that the participants saved, so we could not capture data like how they freely tested the robots, how frequently and for how long they engaged with a certain tactor. Future software could address them by storing all operations at a certain period. The unsupervised study with no video recording provided a comfortable space, but some nuanced data was missed. For instance, we could not observe participants' behaviors (e.g., their facial expressions when perceiving a touch) in the experiment. Novel methods to capture those subtle but interesting details in an acceptable and non-intrusive way are needed.

7 DESIGN IMPLICATIONS

Reflecting on our generative discussion with participants, we present two design implications. These implications aim to inspire future research on alternative opportunities of emotional robotic touch and expand the design space.

7.1 Enhancing Ambiguity

Following Pierce et al.'s definition [55], we aim for a design environment that supports expressed or artistic ambiguity as a "deliberate and potentially valuable quality of design [20]," where "grappling with ambivalent aims and impulses is an intended and desired response from the participant." For exploring emotional robotic touch, we recommend enhancing such ambiguity while leveraging contextualization and respecting individuality.

7.1.1 Beyond Social Gestures. While all robotic touch sensations were perceived as novel, Rub Tactor, the most different from human hand performance, gained the most interest. As its feeling was hard to predict, participants were surprised by how expressive and intimate the sensation could be. More sensations (e.g., tickling, tingling) were suggested to be feasible to create by using similar notions (Fig. 7). The delight that surprising haptic sensations can evoke inspired us to encourage more alternative and unexpected touch explorations, for instance, by discovering and utilizing tactile illusions. For recreating social touch, Nunez and Culbertson [53] previously used sequential normal indentation to create stroke sensations inspired by "the cutaneous rabbit" effect [21]. Tricking human perception to create social cues that are both distinguishable yet unpredictable has great potential to unfamiliar the familiarity, which can trigger curiosity and prolong the sense-making process to evoke more profound reflective understanding [65, 72].

7.1.2 Beyond Machine-like. Participants appreciated our motivation in keeping the *otherness* of the robotic touch, while they suggested that being "machine-like" (e.g., rigid plastic or metal shells [66]) could also be a stereotype of being "other." Instead, they suggested exploring more modalities and textures, adding to the current haptic feedback. The proposed modalities included temperature, softness, roughness, and stickiness. It would be interesting to investigate the *otherness* and *creepiness* threshold to find an acceptable and imagination provokable design region. Many participants mentioned the attempts to apply other textures on TactorBots for new features, especially everyday materials like textiles. Although we had participants test putting the module on top of the clothes (Fig. 9d), no one explored it in-depth. We believe it was because collecting all those materials would be an extra workload, and the current hardware sets were well packaged with no indication of inviting customization. Future work could include those customizable materials in the kit to encourage the experiments.

7.1.3 Beyond Primary Emotions. Our fictional narrative puts all the communicable primary and prosocial emotions from prior studies [25, 26, 30, 82] into one storyline. Although many participants enjoyed the story and could immerse themselves in the plot, we knew how unnatural or challenging it was in story weaving. It was because human emotions could never be that straightforward in real life. We indeed had one participant (P13) who tried to quantify her emotional interpretation, "*I tried to understand if what I felt was* *evoking happiness for me. Sometimes I thought it was evoking 70% happiness, so I will try to tweak the parameters more to hit 100%.*" We joked that she performed like a computer vision robot that measured human facial expressions with percentages. However, the meaningful signals in natural communication could not always be mapped to the primary emotions. In real-life use cases, the meaning of the haptic cues can be more nuanced. Thus, we appeal to leverage contextualization and individuality. While designing communicative haptic cues is essential in the community, we should also allow open-ended expressive touch and embrace alternative metaphors and understandings emerging on the receiver side. Similar to how audiences may appreciate an artwork echoing back to our "emotional haptic canvas" concept. Our designer participant (P3) also emphasized that instead of educating the preset meaning of their designed touch, they are more interested in seeking resonances.

7.2 Shifting Mindsets

7.2.1 Re-evaluate Touch Imagination. While we supposed directly experiencing contact was key in haptic design, human imagination on the tactile channel is much more powerful, which shifted our mindsets. Though not as straightforward as visual imagination or speaking voice in mind, humans can indeed imagine tactile feelings. We hypothesize this is because of the memory of touch and the synesthesia phenomenon. Some participants recalled the scenes visually in their minds where they received a touch from a person with emotional signals. Their memories of the on-skin perceptions might also be evoked. Similar tactile memories can happen in everyday experiences when interacting with animals, environment, and objects. As for synesthesia, a well-known example is "phantom touch" [57]. In our design experiment, participants showed their talent for tactilizing metaphors that include no "touch" information in a design environment. For instance, the building up and suddenly exploding metaphor for Anger pictured by P8 as a cartoon character with steam coming out of its ear and P7 as an abstract concept was tactilized by using TactorBots. When they explained their design inspiration to us, surprisingly, we could also have immediate imaginations of such feeling haptically (Fig. 10). As synesthesia has already played a significant role in the arts [47], such as the metaphors in poetry, we appeal to exploring and utilizing it in future haptic design to foster creativity.

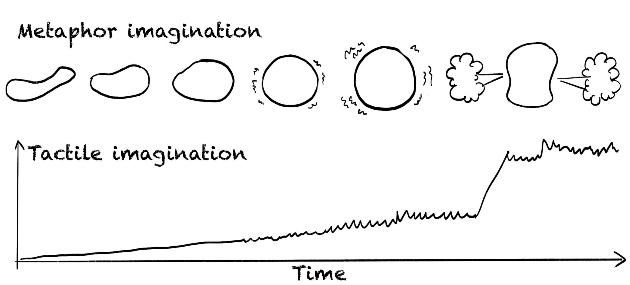


Figure 10: The metaphor of building up and suddenly exploding metaphor for Anger can be easily translate to tactile pattern

7.2.2 Introduce New Perspectives. Having invited different experts to our design exploration, we observed how the experiment shifted their mindsets towards the touch and how their unique perspectives brought us novel inspirations. In our pre-task interview, we had a question about their initial understanding of emotional touch. Most of them had never consciously thought about this, as touch was the second nature of their intuitive behaviors. In the post-task interview, they brought out inspiring designs and thoughtful reflections. Their process of making sense of novel haptic stimulations by associating to their histories or imaginations made touch memorable and meaningful. The enhanced awareness of the bodily sensory capability could help them live more consciously, especially in tactility.

Participants also shared how they would incorporate emotional haptics into their practices. The designer in the museum thought it could greatly enrich the multisensory experience in installation design that could be both engaging and accessible. One technical haptic researcher mentioned that due to his background and rational personality, he had a hard time in the study changing his mindset from focusing on the mechanism to the hidden and ambiguous emotional signals. However, at the end of the interview, he told us this unique experience made him start to value the user's emotional interpretation, which he would consider more in future haptic studies. HRI researchers planned to add the haptic layer to their future design of social robots. The psychology and neurophysiology researchers raised questions for future investigation. For instance, how would the metaphor's scale or gender impact the touch imagination and tactile design? Are there any pop-culture-generated memories that will impact people's metaphors (e.g., many participants pictured Disney movies)? All those insights revealed the importance of inviting new audiences to emotional robotic touch and bridging different communities.

8 CONCLUSION

We present TactorBots, an open-source haptic toolkit for designing emotional robotic touch. We aim to expand the design space by leveraging the ambiguity and *otherness* of the robotic touch to provoke alternative interpretations and new design opportunities. Inspired by psychological findings on interpersonal emotional interactions, we employ gesture-based haptic technology as the starting point. To keep the *otherness* feature, we design the tactor modules with a minimalist form, which are shaped purely based on their purpose functions. This paper foregrounded the motivation and design process of TactorBots. The longitudinal out-of-lab design exploration with 13 participants revealed the qualities of emotional haptic design with TactorBots, including reflective perception, alternative interpretations, and creative imaginations inspired by intentionally designed *otherness* and intuitively employed practices. Based on the feedback from our participants, we provide suggestions and implications for further investigations. Our long-term design exploration is continuing. With TactorBots as an ideation prop, the same group of participants is engaged in a co-speculation on envisioning what the next generation's emotional haptic system will be like and how it can be integrated into everyday scenarios.

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A LAB STUDY WITH EARLY PROTOTYPE

The formative perception study had two sessions: ***(1) Gesture Identification Session:*** find out how participants perceive and identify the touch gestures rendered by mechanical tactors; ***(2) Placement Investigation Session:*** instruct participants to suggest the appropriate contact location for each gesture by physically exploring the placement with our test interface.

Table 3: List of explored social gestures in this work.

Gesture	Description
Hit	Strike sharply with the palm or fist
Pat	Touch gently with the flat of the hand
Push	Exert force on other's arm to move it away from oneself
Rub	Rapid back and forth motion with firm pressure
Shake	Limb swings with the shaking gesture under natural conditions
Squeeze	Performed on the lateral of the forearm with significant level of pressure
Stroke	Gentle, continuous gesture with a large range of motion on the skin
Tap	Strike lightly with a small contact point
Tremble	Move involuntarily, usually happens together with other gestures

A.1 Method

Participants. We invited 12 participants (7 Female, 4 Male, 1 Other) aged between 22 to 30 years old (M = 24.83, SD = 2.03).

Gesture Identification Session. On arrival, the participant sat at a table with the testing setting and received the study instructions. The study protocols included: (1) Demo of studied gestures: the researcher performed all the gestures with their hand and forearm (Fig. 2) to inform the gesture definitions. (2) In the study, the participant was blindfolded, wore noise-canceling headphones, and placed their left forearm on the testing interface. (3) Familiarization: the researcher ran through all gestures at a fast speed (5s/gesture) on the participant's forearm. (4) Researchers started to run the nine predefined touch behaviors in random order by manually changing the tactor module and triggering the function. Each behavior was performed for 15s. (5) After each round, the participant was asked to make a choice from the nine gestures on the response sheet.

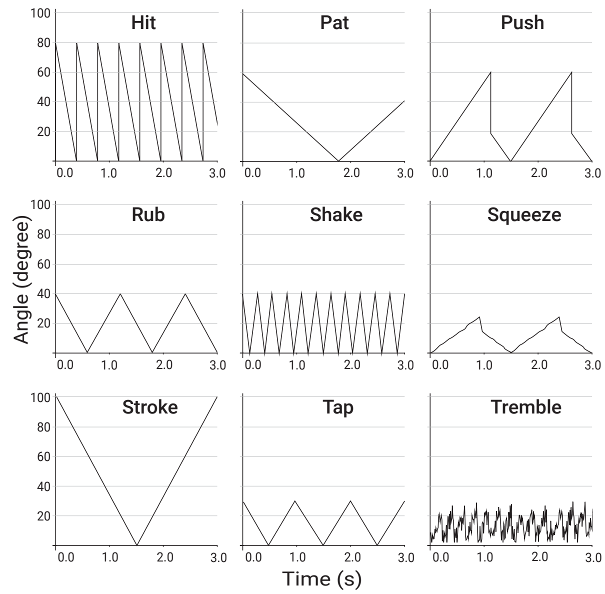

Figure 11: Line graph shows the rotational angle changes along with time for each gesture to visualize the motion functions

Placement Investigation Session. This session was conducted after finishing the first session with the results saved. The study protocols were: (1) Following the random order in the last session, the participant was introduced to the target gesture for each tactor. (2) The introduced tactor was activated. The participant was asked to explore and report where they would like to get this stimulation along their forearm. They could place the tactor on either side of the slider and slide it on the rail. (3) The researcher documented the results by measuring the position of the motor shaft.

A.2 Results

Gesture Identification Session. Figure 13 shows the results of the perception study. Overall, the participants were able to correctly identify the touch gesture with high accuracy (M = 83.4%, SD = 0.16). For gestures such as push, rub, shake, squeeze, and stroke, people can decode them with over 90% accuracy. In the matrix, we noticed the confusion mainly lay between pat & hit, pat & tap, which could be due to the similar features of the gestures. Pat and Hit share the same tactor. Although the predefined Hit behavior ran much faster than Pat, the post-study interview showed that "the hit function was still too gentle." Pat and Tap were both moved up and down above the forearm. Despite the Tap tactor being designed with less contact area and the function having a higher frequency compared to Pat, participants commented, "the differences in the contact area were not noticeable enough." We hypothesize that the Pat tactor was designed in a relatively flat shape. It cannot provide entire contact when applied to the rounded-shaped forearm. In our design of the final robotic modules, we focus on refining the Pat/Hit and Tap

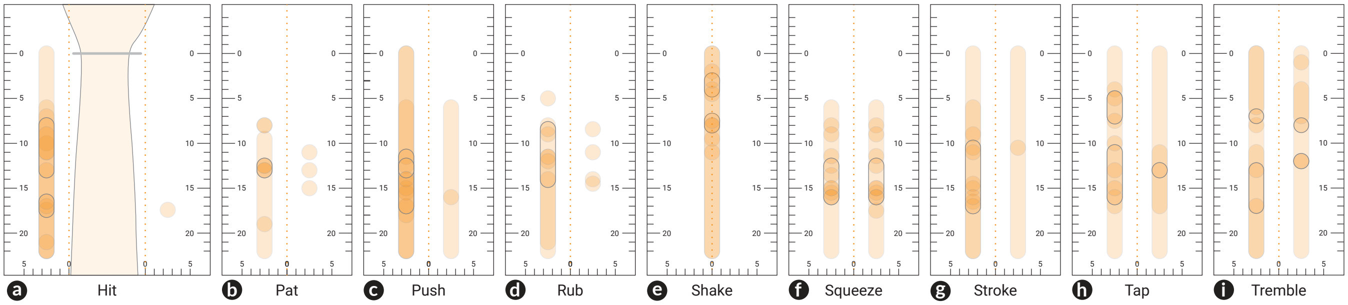

Figure 12: Results of appropriate touch contact location for each robotic social gesture in the placement investigation

tactors. Furthermore, participants showed interest and amazement after finishing the study. One participant said: "*The sensations were so natural and easy to understand. They were really distinct from each other. It is hard to imagine that they were all rendered by one micro servo.*" We were encouraged by those study results and decided to continue using 1DoF servo-driven fashion with 3D printing to build our robotic haptic toolkit.

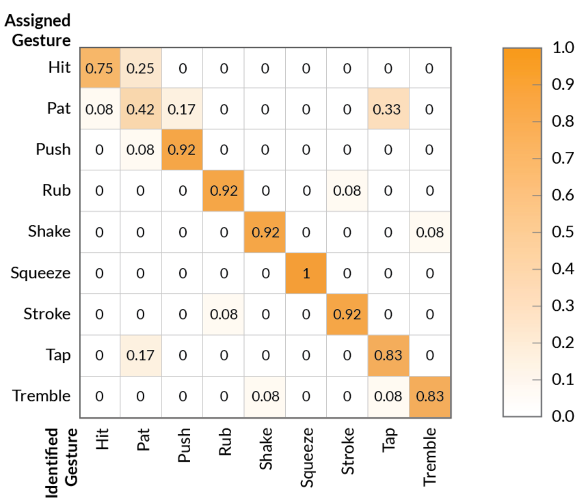

Figure 13: Confusion matrix showing percentage accuracy of the interpretation for the robotic social touch

Placement Investigation Session. Figure 12 and Table 4 show the results of appropriate touch contact location for each robotic gesture. Some participants provided a certain contact spot, while others provided a range of space. We noticed that some people did not care about the placement of some tactors. For instance, some of them told us that all forearm areas were okay with certain tactors after sliding them from wrist to elbow (see some large range highlights in Fig. 12). Others were very particular about it and tested them carefully, sliding back and forth, trying to tell the difference between various touch areas, and providing a point that they felt to be most appropriate. In Figure 12, the darker the pattern color (orange) was, the more popular the location was chosen. The recommended range from the study results was highlighted with the black stroke pattern in Figure 12 and Table 4. Our results indicated that participants were more willing to place the tactors in an area about 12-17 cm away from the wrist. They commented that the muscle (brachioradialis) was strong there, which made them feel more secure and comfortable to be touched on, especially for intense gestures such as push. Moreover, the layer with thicker muscle allowed a more significant skin deformation when encountering normal force, which led to a more perceptible sensation. Thus, Squeeze was also suggested to be performed closer to the elbow. Shake (Fig. 12f), however, could be more appropriate to perceive near the wrist, as the thinner wrist left more space for movement, and the users hoped to let their forearms sway with the tactor motion more freely. For most gestures, participants prefer to place the tactor modules over the arm's external side (left side in the diagram, Fig. 12). They suggested that receiving touch from the external side was more common in interpersonal interaction. But for the behaviors that mostly applied to the dorsum of the forearm other than the lateral sides, such as pat, hit, and tap, they said it was fine to be performed from both sides.

Table 4: Appropriate contact position for each social touch gesture (range here indicates the distance between wrist and the tactor's shaft)

Gesture	Side	Range preference (cm)
Hit	External side	7-14 / 16-18
Pat	External side	12-14
Push	External side	11-18
Rub	External side	11-18
Shake	Center	2-5 / 7-9
Squeeze	Both sides	12-17
Stroke	External side	10-18
Tap	Both sides	4-8 / 10-17(external), 13(inner)
Tremble	Both sides	6 / 10-18(external), 8 / 12(inner)

B PARAMETERS ON TACTORBOTS APP

When assembling the tactors, we set the servo (except Stroke) to 180 degrees and attach the tactor to the servo shaft in the vertically upward direction. Adjustable parameters on TactorBots Software include:

- ***Touch range:*** Tactor's rotational range. You can control the minimum (touch) and maximum (retreat) range with the slider.
- ***Time of touching:*** The amount of time when the tactor moves from the maximum range to the minimum range, actually controls the touching speed.
- ***Time of retreating:*** The amount of time when the tactor moves from the minimum to the maximum range, actually controls the retreating speed.
- ***Touch randomness:*** Adding randomness in the rotating movement, which can create vibration effects and simulate the trembling stimulation
- ***Contact duration:*** The duration that the tactor will hold on to the minimum range position until the next round of retreating
- ***Touch interval:*** The duration that the tactor will hold on to the maximum range position until the next round of touching

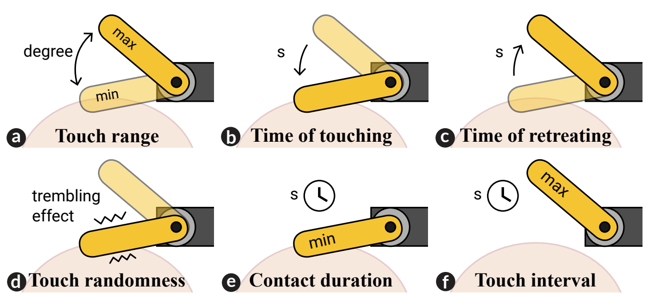

Figure 14: Adjustable parameters in designing the robotic touches on the TactorBots software

C OUT-OF-LAB DESIGN EXPLORATION

C.1 Text-based Story in Design Task

Jean wants to design haptic feedback with wearable devices to create an immersive experience for a haunted house amusement ride. It is in a cursed bracelet that talks to the visitor and tells them scary stories as it guides them through the house. Jean's idea is that at certain spooky points in the tour, the bracelet that the audiences wear will evoke an emotion to make the tour more engaging. Can you help her design the haptic sensations with TactorBots based on the scenarios?

When starting the adventure, you are in a dark space without any light. You can only hear some creepy sounds from a distance. The elf in the bracelet is scared (***please design a haptic sensation that enables the elf to express FEAR through the bracelet and save the sensation by naming it "Fear_1"***). Suddenly, a gentle wind blows and a dim light descends from the top. You realize there is a boat in the cave. The elf guides you to go onboard. Once you sit in the boat, you can hear the sound of water touching the shore. After a while, the river formed. You can row the oars to let the ship move forward. The first scene you encounter is "wild greed". There are many huge and ugly monsters coming out of a thorn bush. They have a foul smell and you can even see blood at the corner. The elf cannot tolerate that (***please design a haptic cue to express DISGUST and name it "Disgust_1"***) so he urges you to row faster to get rid of them. Then, you come into the "forest of envy". It is a forest with no leaves. On the branches, there are envious eyes blinking in the red color. You can hear endless harsh curse words, which remind the elf of the time he got trapped into the bracelet (***please design a haptic cue to express ANGER and name it "Anger_1"***). After getting out of the forest, you arrive in the "swamp of agony". There are many bubbles each with a different scene playing in them. The first bubble that bursts shows how a bird was dead while trying to open a cursed bracelet. The accompanying elf tells you sadly that she was his friend who was attempting to rescue him (***please design a haptic cue to express SADNESS and name it "Sadness_1"***). The following bubbles showed how humanity ruined or killed each other due to all those evils released from Pandora's box. Those scenes are too cruel so the elf wants to comfort you (***please design a haptic cue to express SYMPATHY and name it "Sympathy_1"***).

To escape from the dangerous cave, you need to vanquish the dragons that block your way. (The 1000-word fighting scenery is omitted here...) Once you win, you will enter a garden where all the tulips are in full blossom. The elf is so happy about getting rid of the scary cave and delighted by the fragrance of flowers (***please design a haptic cue to express HAPPINESS and name it "Happiness_1"***). While exploring in the garden, you notice a bunny is sitting in the grass, watching you. The elf tells you that it is his best friend, who can help with releasing him from the cursed bracelet. He really appreciates you for saving him and helping him to find the bunny (***please design a haptic cue to express GRATITUDE and name it "Gratitude_1"***). Right before you are about to take off the bracelet and give it to the bunny, the elf stops you. He says, "You are also my best friend now! I will remember you and come to find you once I am out, wait for me! (***please design a haptic cue to express LOVE and name it "Love_1"***).

Table 5: Design decision of selected Tactors for each emotion

	Fea	Dis	Ang	Sad	Sym	Hap	Gra	Lov
P1	Squ	Tap	Hit	Pat	Rub	Sha	Pat	Rub
P2	Squ	Pus	Squ	Pat	Rub	Str	Tap	Rub
P3	Tap	Rub	Hit	Pus	Squ	Sha	Sha	Squ
P4	Pus	Sha	Squ	Str	Tap	Pat	Pus	Rub
P5	Hit	Str	Tap	Squ	Squ	Str	Sha	Pat
P6	Squ	Str	Hit	Squ	Pat	Rub	Tap	Rub
P7	Squ	Pus	Hit	Pat	Sha	Squ	Tap	Squ
P8	Squ	Sha	Pus	Str	Pat	Sha	Tap	Squ
P9	Squ	Pus	Hit	Squ	Tap	Rub	Pat	Rub
P10	Sha	Str	Hit	Rub	Pat	Sha	Squ	Rub
P11	Squ	Str	Sha	Rub	Pat	Tap	Sha	Squ
P12	Tap	Squ	Hit	Pus	Pus	Sha	Pat	Squ
P13	Pat	Squ	Hit	Tap	Sha	Pus	Rub	Rub