Transforcers: Exploring Information Communication through Surface-based Force Interactions

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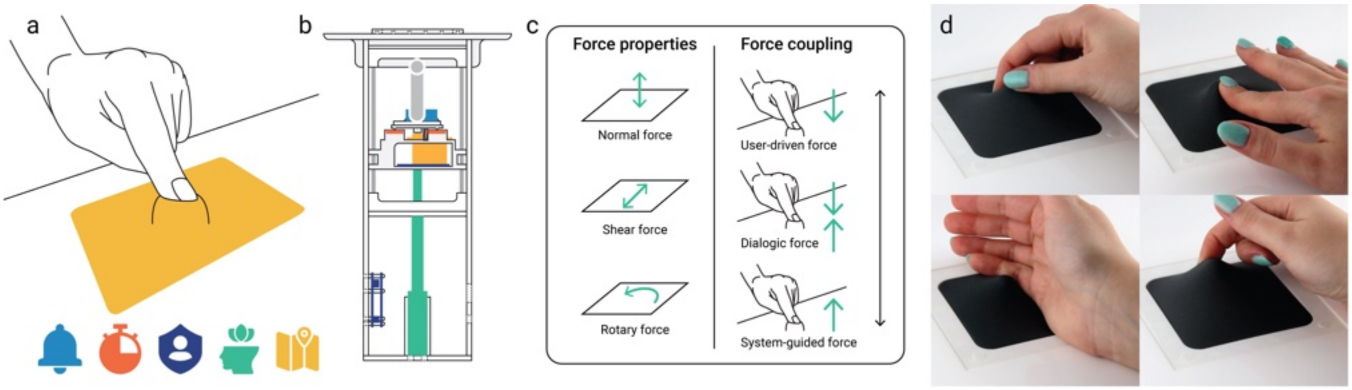

Figure 1: Overview of the Transforcer system and design approach: (a) the five scenarios studied, (b) a diagram of the Transforcer prototype, (c) an excerpt of the force design space illustrating key force properties and couplings used across the scenarios, and (d) exemplar interactions showing how participants engaged with the Transforcer through force-based actions, such as grabbing, pushing, stroking, and pulling.

Abstract

In the physical world, the force required to interact with an object provides rich information about its material properties and intended use: some objects deform easily when force is applied (e.g. a pillow) while others resist our attempts (e.g. a spring). Recent advances in haptic technology support integrating force modalities into interactive surfaces, presenting novel ways to convey material properties and create engaging experiences. However, little is known about how people perceive and interpret surface-based force interactions. To address this, we designed the Transforcer, a device generating normal, shear, and rotational forces, and studied user perceptions in different scenarios. Our findings show that force is experienced as a multi-layered interaction: bodily perception grounds interpretation, material qualities convey intent and control, and meaningful interactions emerge when body, task, and system align. We contribute (i) a design space of surface-based force interactions; (ii) the design and implementation of the Transforcer; (iii) findings from a semi-structured interview study; and (iv) design recommendations.

CCS Concepts

• **Human-centered computing** → **Haptic devices**; **Empirical studies in HCI**.

Keywords

Haptics, Force Feedback, Force-Based Interactions, Information Communication

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1 Introduction

In the physical world, the force we apply to an object during interaction provides rich information about it's material properties and intention of use. It conveys constraints and affordances, like the two-step feedback of a camera shutter button—lightly pressing to focus

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and firmly pressing to take a photo—compared to the purely graphical and touch-based interaction of a mobile phone camera. With recent advancements in haptic technology—including mid-air haptics [8], pin-array and deformable force-feedback surfaces [26, 30], wearable haptic suits [46] and authoring tools for haptic force feedback [48]—integrating force modalities within interactive systems has opened new possibilities for conveying information and creating engaging user experiences. For example, a mobile device could signal a private message through gentle taps or an alarm through sharp, rhythmic knocks, allowing it to be silenced by striking the device like a traditional two-bell clock.

Despite the potential of surface-based force modalities, it remains unclear how they can encode different forms of information and how this is interpreted and perceived by users. Research on cross-modal correspondences has begun to investigate how deformable shapes relate to human senses and affect, for instance shape-change magnitude and frequency with emotion [13], correspondences with sounds [31], and associations with color and emotion [42]. However, beyond these fundamental investigations, how individuals interpret force-based interactions in different scenarios and contexts remains unexplored. Addressing this gap is important as it could lead to more intuitive and satisfying user experiences across various applications, from virtual reality [4] to data visualization [55]. By better understanding how these qualities can be effectively translated into technology, we can enhance the utility and usability of force feedback in interactive systems, in essence: *How can the affordances and cues of everyday tangible interactions inform the design of surface-based force interactions?*

At a fundamental level, surface-based force interaction is inherently bidirectional (in contrast to visual and auditory modalities) increasing the complexity of constructing and understanding the user's experience. Force applied by a surface to a user's finger can be passively sensed by the user or actively resisted. The level of participation of the user in this interaction significantly changes their perception and interpretation of the provided feedback. The reverse also applies when a user applies force to a surface.

Understanding this complex interaction space therefore requires drawing on insights from multiple fields. Haptic research provides the basis for understanding how to design and fabricate force feedback for physical interfaces, encompassing interaction modalities [11], fabrication techniques for creating passive objects with customized haptic capabilities [e.g., 24, 50, 56], interface tools that enable others to create haptic designs [48], and dynamic force interaction devices, including surface-based systems such as inFORCE [26] and FluxTangible [19], as well as handheld VR controllers [4] and shape-changing knobs [49]. Physicalization research offers insights into encoding data through physical forms [21] and the implications of interactions for the underlying data [35]. Finally, shape-changing interfaces inform us about interaction directness and the dual role of physical changes as both input and output [32].

Despite this significant and diverse study, there is no holistic understanding of how multiple types of force feedback are perceived and understood in surface-based force interaction. This paper aims to fill this knowledge gap.

To explore these concepts, we synthesized a design space for surface-based force interaction, which we call the *Force Pixel* design space. Just as a graphical pixel is the smallest unit of a visual display, a force pixel represents a fundamental unit of interactions in a force-based system. To move beyond touch-based or purely visual interfaces, we ground our design space in the physics of mechanical force as a basis for interaction. Mechanical forces are familiar through everyday physical sensation and bodily experience, making them a useful starting point for designing intuitive force-based input and feedback.

We used this design space to inform the design of a force input and output device—the Transforcer—capable of generating normal force, shear force, and torsion (Figure 1). The Transforcer functions as a single, interactive force pixel, responding directly to how users apply these forces. This allowed us to investigate both direct interactions, in which users physically manipulate the force pixel itself to control or access digital content, and indirect interactions, in which force output communicates system state or information without directly manipulating the underlying content. Using this interaction space, we designed five scenarios that we used as experiential prototypes in semi-structured interviews to elicit user perceptions, interpretations, and understandings of force interactions.

We found that force interaction is experienced as a multi-layered phenomenon. Participants grounded their interpretations in bodily perception, drew on the dynamic qualities of force—such as resistance, directionality, and movement—to infer intent and control, and constructed meaning through evolving mappings between force, task, and context. Force was experienced as a relational and negotiated interaction in which effective interactions emerged when bodily, material, and conceptual layers aligned, while misalignment required participants to actively renegotiate meaning.

To summarize, the contributions of this paper are: (i) a design space of surface-based force interactions; (ii) the design and implementation of the Transforcer; (iii) results of a semi-structured interview study with an experiential prototype; and (iv) a series of design takeaways for surface-based force interactions.

2 Related Work

Force-based interactions are widely studied in Haptics and HCI literature. We specifically only cover the most relevant of this work—that on *surface-based* force interaction—covering definitions, human proprioception, devices for producing force interactions, and human perceptions of force.

2.1 Surface-based Force Interaction

This work focuses on surface-based force interactions: both force-input and force-feedback that occur on *surfaces* [e.g., 26, 30]—either rigid or compliant areas where the user places or presses their fingers or hand in order to interact with the force modality. This is in contrast to other approaches to delivering force interactions where devices are hand-held [e.g., 4, 17], attached to the body as wearables [e.g., 1, 36] or full-body suits [e.g., 46], or operate in mid-air [e.g., 8]. Uniquely, force interaction on surfaces differs from many of these other approaches in that by moving the position of the hand or finger the user is in full control of how and when force is applied and the extent to which it is felt [30].

Force feedback is information gathered through our kinaesthetic sensory system—the sense of position and motion of the limbs [40]; while force input uses the position and motion of limbs to provide input to an interactive system. Force is differentiated from pressure in that it is a vector—it has both an magnitude and a direction—while pressure is a scalar quantity measuring force applied over an area ($P = \frac{F}{A}$, where $P = Pressure$, $F = Force$, and $A = Area$). In terms of input, this makes force a more expressive (but more complex) measure than pressure.

We can both sense and produce three core types of force: normal force (force that is perpendicular to a surface), shear force (force that includes a horizontal element in its applied direction) and torsional force (twisting or rotational force around an axis) [29]. There are numerous examples of systems that exploit these forces as an input modality. Normal force is used for interactions on phones [18, 54] and trackpads [33], while 2D shear has increased the input bandwidth on mobile devices [16, 47]. Such interactions facilitate novel and more expressive interactions, increasing the bandwidth of communication [28]. While full shear input is possible on deformable devices [5] it is not readily measured or applied in interaction. Rotational actions are commonly used on multi-touch devices, but few, if any, incorporate a force component.

Surface-based force feedback at the pixel level is most often seen in shape-changing interfaces [3, 32, 43] where elements extrude from a surface to apply normal force onto the user's fingers or hands. Examples of these interfaces that are explicitly designed to apply force include inFORCE [26] and Haptic Edge Displays [20], while data physicalizations [21] such as EMERGE [44, 45] and ShapeClip [15] incidentally provide surface-based normal force feedback. In contrast, the whole surface of a device can move to apply force onto the user's fingers (again, producing normal force), for example TouchMover [38, 39] or KinesTouch [9] both actuate a touchscreen to enhance interaction.

In contrast, the Transforcer was explicitly constructed as a fully-functional artifact that would allow us to holistically explore surface-based force interaction design. Its core novelty lies in the three types of force the single pixel can produce—normal, shear, and rotary—this goes beyond any of the previous surface-based force examples in the literature that only address a single type of force feedback.

2.2 Perception of Force

The novelty of surface-based force as an interaction modality has required researchers to engineer new hardware approaches and interaction techniques to prototype and understand the interaction space. The requirement to justify the use of the force modality has almost exclusively fallen to seeking performance advantage [e.g., 14, 28, 54], with qualitative perceptions typically following as secondary measures, leaving a significant gap in our understanding of the perception of force.

Of the work that does address perception of force, we identified focused studies on specific elements of force-based interactions, for example it is recognized that force feedback from a button press is a psychological cue that signifies action, confirmation, or control [23, 34]. More recently, fundamental perceptual studies have understood the cross-modal correspondences between force input and colors and shapes [41], emotions [42], and sounds [31]. To the best of our knowledge similar studies for force feedback have not yet been conducted.

Adjacent, non-surface based fields of force-based study provide motivation for surface-based perceptual study. For example, CapstanCrunch (a handheld, VR grip-based device) found that users' paid more attention to their force when compressing an object than when relaxing their grip [37]. While studies with Haptic Revolver, a handheld VR haptic feedback device, found that increasing the realism of feedback does not necessarily mean an improved user experience [53]. EMS-based force-feedback in Mixed Reality identified the need for realistic mapping between rendered forces and those expected in the real-world environment [25]. Finally, studies with Elastilinks identified motor latency as a core limitation in any motor-centric force-feedback device. This has the potential to impact on user experience and perception of resulting force outputs, especially in cases of consecutive force output [51].

Even with these studies as a starting point, there is still no holistic understanding of users' perceptions of force input and output and how this changes their interpretations and interactions with force-based interactive devices. Hence, this paper aims to address this gap by developing knowledge and guidance for creating and engaging with such interfaces.

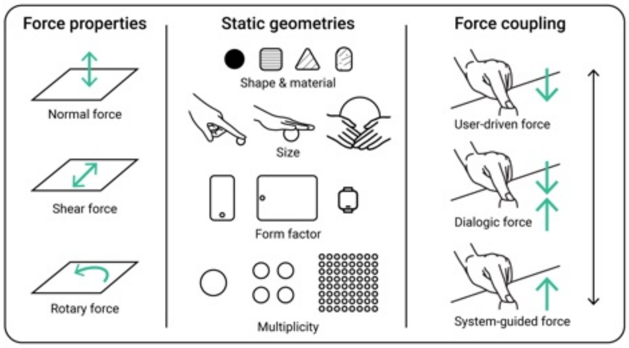

Figure 2: Force Pixel design space, including force properties (normal, shear, and rotary force), static geometries (such as shape, material, size, form factor, and multiplicity), and force coupling (user-driven, dialogic, or system-guided force).

3 Force Pixel Design space

The Force Pixel design space (Figure 2) delineates key dimensions of the smallest unit of surface-based force interaction, spanning physical properties, material configurations, and the dynamics between user and system. It builds on prior work in force-based, tangible, and shape-changing interaction (e.g. [12, 27, 32]), while extending these perspectives to account specifically for surface-based force as both an input and output modality.

The design space was developed through a synthesis of prior literature on force-feedback and interactive physical interfaces, combined with our own design reflections on what constitutes the smallest meaningful unit of force interaction on a surface. As such, it is intended as a conceptual and generative framework to guide design and analysis, rather than an exhaustive taxonomy or fully empirically validated model. Below, we outline the foundational aspects that define a force pixel and guide its design. Together, these dimensions capture how force is generated, perceived, and negotiated during interaction:

3.1 Force Properties

Force properties reflect recurring mechanically distinct forms of force actuation and perception identified in prior work, which we abstract here into three fundamental force types that can be expressed and perceived through interactive surfaces: normal [e.g., 26], shear [e.g., 16], and rotary (torsional) force [e.g., 29]. Each represents a distinct physical relationship between the user and the surface, and supports different interaction possibilities. While described here individually, these force types can also be combined, allowing compound force expressions (e.g. normal force with simultaneous torsion) that expand the expressive range of force-based interactions.

3.1.1 Normal force. Normal force involves force applied perpendicular to a surface, resulting in vertical movement [e.g., 26, 29, 30]. It supports interactions ranging from light contact to heavy pressing, and can be used both as user input (e.g. pressing into a surface) and system output (e.g. a surface pushing back).

3.1.2 Shear force. Shear force involves lateral movement parallel to a surface, such as sliding or dragging [e.g., 16, 29, 52]. This force supports interactions based on horizontal displacement, including guided motion, texture exploration, or directional feedback. Shear force may be user-generated, for example through deliberate sliding or dragging gestures, or system-generated, where lateral force guides or resists sideways movement.

3.1.3 Rotary (torsional) force. Rotary force introduces twisting or rotational movement around an axis [e.g., 29]. This enables angular interactions such as turning, steering, or resistance-based rotation, extending force interaction beyond linear motion. Again, this can be user-applied, such as twisting to adjust a parameter, or system-applied, like rotational resistance or motion.

3.2 Static Geometries

Static geometries describe the physical characteristics of the interactive surface, including shape, size, material, form factor, and pixel multiplicity—drawing on established physical design considerations in interactive systems [e.g., 12, 27]. These properties influence how force is applied, perceived, and interpreted, and shape users' expectations before interaction begins. As in other physical and tangible design spaces [e.g., 12, 27], geometry acts as a foundational layer that constrains and enables interaction, mediating how force properties and dynamics are experienced. For example, shape and material affect cutaneous perception at the point of contact, while size influences whether interaction is invited through a fingertip, the palm, or even both hands. Form factor further situates force interaction in relation to the body, such as when embedded in personal devices, tablets, or wearables. Finally, multiplicity shapes both the spatial resolution of force feedback and the kinds of interactions that become possible; it may be expressed through a single pixel, subdivided into quadrants, or distributed across multiple pixels in a grid (e.g. as in prior work on multi-point force interaction [26, 30]).

3.3 Force Coupling

Force coupling describes how user-applied force and system-generated force relate to one another over time, extending prior work that treats force not only as input or output, but as a negotiated interaction [e.g., 26, 32]. Unlike visual or auditory feedback, force interaction is inherently bidirectional: users act on the system through force, while the system simultaneously responds through physical resistance, motion, or constraint. We distinguish three forms of coupling, which are not mutually exclusive categories but rather a spectrum of interaction possibilities:

3.3.1 User-driven force. In user-driven interactions, force is primarily applied by the user to directly accomplish a task. The system responds, but does not actively guide or constrain the interaction beyond basic feedback. This coupling emphasizes agency and intentionality, with force acting as a means of executing a decision or action.

3.3.2 System-guided force. In system-guided interactions, force is primarily generated by the system to communicate information to the user. User input may be minimal or limited to initiating or acknowledging the interaction. Here, force acts as an output modality, conveying state, direction, or rhythm through physical motion or resistance.

3.3.3 Dialogic force. Between these extremes lies dialogic force interaction, in which user and system reciprocally respond to one another through force over time. This exchange can take place simultaneously, for example when both contribute force at once/contribute to the same movement, or sequentially, when one reacts to the other's prior action. In these interactions, neither user nor system fully determines the outcome alone; instead, meaning and progress emerge through ongoing physical negotiation. Dialogic force highlights force as a conversational medium, where resistance, motion, and timing form a feedback loop that evolves over time.

4 Design

We designed the Transforcer (Figure 3) as an experiential device to explore selected dimensions of the Force Pixel design space through direct engagement with surface-based force interactions. As no single prototype can meaningfully instantiate the full breadth of the design space, we deliberately scoped the Transforcer to explore force properties and force coupling (Figure 2), while not systematically investigating static geometries. This allowed us to focus on force interaction in a device-agnostic and exploratory way, rather than on specific material, shape, or technological instantiations.

Its form and capabilities were therefore guided by three core goals: (i) to generate compound force actuations based on the three mechanical force types outlined in the design space (normal, shear, and rotary), (ii) to support dynamic transitions between force modalities over time, and (iii) to enable force interactions with varying force couplings between user and system.

These capabilities allow the Transforcer to support user-driven, system-guided, as well as dialogic interactions in which users alternate between applying force and perceiving system-generated force. As such, the device was designed not to represent the entire design space, but to provide a focused platform for investigating its mechanical and dynamic interaction qualities. The device was intentionally designed as a single, localized interaction surface to foreground force as the primary interaction modality, without relying on visual or auditory cues.

4.1 Implementation

The Transforcer (Figure 3) consists of a small platform on which the user can place the palm of their hand. Users rest their forearm on the table stand with the wrist in a neutral position, and place their dominant hand over a 80×80mm opening covered by a soft, stretchable fabric membrane. Interaction occurs through this membrane, which transmits forces safely while concealing the underlying mechanism.

Beneath the opening, three actuators generate normal, shear, and rotational forces corresponding to the three force properties in the design space. The magnitude and temporal behavior of each force modality can be adjusted independently by varying actuator amplitude and speed. All forces are within safe limits yet easily detectable by the human hand.

4.1.1 Actuation & sensing. Mechanical force is generated using three actuators: a 100mm linear actuator (L16-100-35-06-R) for normal force, a 360° continuous rotation servo (900-00360) for torsional force, and a 90° micro servo (ADA2307) coupled to a 50mm rod to produce shear force. The actuators are vertically stacked (see Figure 3): the linear actuator (green) sits at the base, the continuous servo (yellow) is mounted on the linear actuator's end effector via the sliding platform, and a disk is mounted on top. The micro servo (light blue) is embedded in this disk, with the rod and its 15×15mm spherical end effector attached. This configuration allows the Transforcer to produce discrete and compound force behaviors, as well as smooth transitions between force modalities.

User interactions are sensed using three co-located FSR sensors (FX293X-100A-0010-L; orange) beneath the continuous servo disk. The system continuously monitors these sensors, calculating a combined value to represent the overall force. Deviations from this baseline indicate user input, and by comparing the relative readings of each sensor with the known actuator positions, the system can infer the direction and magnitude of user-applied force. Different scenarios and tasks define distinct thresholds for force magnitude and direction, ensuring that actuator responses are triggered only when the user input meets the requirements of the current behavior.

Force behaviors were informed by prior literature and refined through pilot testing. For instance, insights from Alexander et al. [2] guided the scale, travel distance, resistance, and contact geometry of the rod, ensuring feedback remained within a familiar and comfortable range while still allowing for expressive variation.

5 Methodology

This study explored how users perceive and appropriate surface-based force interactions across the dimensions of force properties (normal, shear, rotary force) and force coupling (user-driven, system-guided, dialogic). We adopted an experiential, scenario-based approach using the Transforcer device to investigate interpretations, mappings, and meaning-making in force-based interactions. Given the exploratory and design-oriented nature of this study, our goal was to elicit rich interpretations and speculative accounts of novel force-based interactions (and not to assess usability or performance).

5.1 Participants

We recruited 12 participants from three different institutions in the United Kingdom through opportunity sampling (4 identified as female, 8 as male) with an average age of 33 years (σ = 8.81). Participants were recruited from Human-Computer Interaction (HCI) and closely related fields, with experience in interactive systems, human-centered design, or prototyping novel interfaces. We intentionally recruited domain experts rather than lay users, as we expected them to more readily move beyond the novelty of the Transforcer device and reflect on how different force properties and couplings could map to broader interaction concepts, application scenarios, and design opportunities.

Inclusion criteria required participants to have relevant expertise in HCI or a similar area, as well as full mobility and functionality of their dominant hand to enable interaction with the Transforcer. Eleven participants identified as right-handed and one as ambidextrous; the ambidextrous participant selected one side from which to interact during the study. For a detailed overview of participants' demographics see Table 1.

5.2 Study Setup

Participants were seated next to the Transforcer device mounted in a table stand, allowing for easy placement on either the right or left side to accommodate handedness (Figure 4). During the study, they were instructed to position their dominant hand over the 80×80mm interaction area, allowing force feedback to be perceived through palm and fingers. The use of a fabric membrane ensured consistent tactile contact while supporting a range of interaction styles, from light touch to grasping and pressing. Participants wore noise-canceling headphones. The researcher delivered instructions through a microphone routed to the headphones to reduce the audible hardware noise.

5.3 Scenarios

To investigate how surface-based force interactions can convey digital concepts and create engaging haptic experiences, we designed five prescribed interaction scenarios using the Transforcer (see Figure 5). These scenarios are not exhaustive but serve as a complementary suite of designed effects, refined by piloting, combining a range of force-based interactions.

The five scenarios were selected not as an exhaustive set, but as a complementary sample intended to span a meaningful range of the design space dimensions explored in this study. Specifically, they were chosen to cover all three force properties (normal, shear, and rotary force) and a range of force couplings (user-driven, system-guided, and dialogic), while keeping static geometries constant through the use of a single prototype. This allowed us to compare how different force dynamics were perceived without variation in form factor, materiality, or multiplicity.

Beyond their mapping to the design space, the scenarios were chosen to reflect a varied yet familiar set of everyday interaction contexts. They span functional, social, and wellbeing-oriented goals,

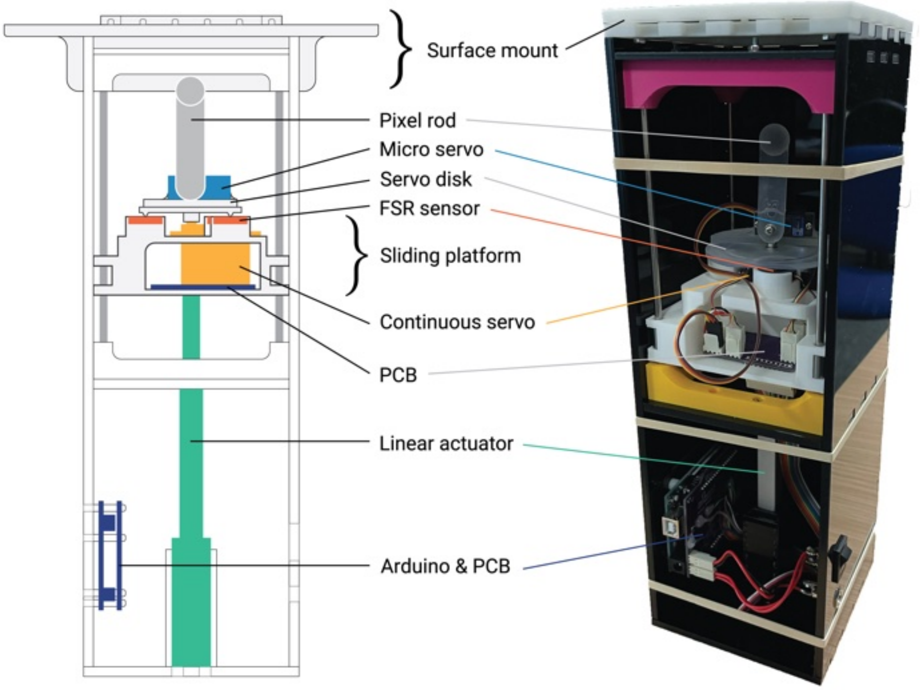

Figure 3: Overview of the Transforcer device.

Table 1: Participant demographics including gender, age, job title, years of experience in HCI, and handedness. *P5 identified as ambidextrous and chose to use their right hand during the study.

Participant	Gender	Age	Job title	Years in HCI	Handedness
P1	Male	30	PhD student	2	Right-handed
P2	Female	26	Postdoctoral researcher	3	Right-handed
P3	Male	28	PhD student	3	Right-handed
P4	Male	27	Postdoctoral researcher	4	Right-handed
P5	Female	52	Associate Professor	7	Ambidextrous*
P6	Male	31	Postdoctoral researcher	3	Right-handed
P7	Female	26	Senior Research Associate	3	Right-handed
P8	Male	31	PhD student	2	Right-handed
P9	Male	42	Lecturer/Assistant Professor	5	Right-handed
P10	Female	35	Research Associate	3	Right-handed
P11	Male	25	PhD student	2	Right-handed
P12	Male	46	Lecturer/Assistant Professor	4	Right-handed

and include both analogue-inspired interactions (e.g. timekeeping and physical navigation) and digitally native ones (e.g. notification management and privacy/security). This diversity was intended to ground the exploration in situations participants could readily relate to, while eliciting reflection on a range of force-based possibilities.

Each interaction was selected and refined based on three key guidelines: (i) exploration of all three force modalities, (ii) bidirectional nature of the interaction, and (iii) use of force as primary feedback layer. The force modalities and couplings involved in each scenario are visualized in Figure 5. A synopsis of each scenario is presented below.

5.3.1 *Time-based Interactions.*

User-driven interactions related to managing and perceiving time, including setting timers, monitoring progress, and stopping alarms. In Time-#1 the user rotates the pixel clockwise to set the time (similar to winding a mechanical timer), with the pixel unwinding counterclockwise as time runs out. In Time-#2 the user pulls the pixel out of the surface to set the duration of the timer. The pixel's height represents the remaining time, gradually sinking back into the surface as time progresses, with a linear motion. As part of the two timer effects, the user can apply force to make real-time adjustments to the remaining time: pull/clockwise shear to add and push/counterclockwise shear to

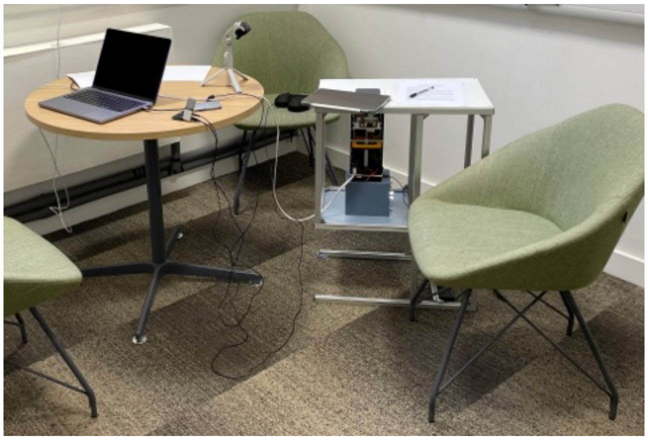

Figure 4: Study setup showing the researcher on the left with a laptop controlling the Transforcer device, which is mounted in a table stand on the right and can be placed on either side of the participant to accommodate handedness.

reduce time. Once either timer effects reach zero, a continuous notification like an alarm (e.g. twin bell simulation) activates, signaling that time has run out.

5.3.2 Privacy and Security. Dialogic interactions designed to make selections and user-driven unlocking. Privacy-#1 introduces varying levels of resistance to simulate negotiation and commitment during user selections. Affirmation (#1a) requires a single strong push to flick the lever into position, supporting low-risks confirmations. Persistence (#1b) requires sustained force across the full range of motion, returning to its original position if released prematurely. Friction (#1c) causes the lever to flick back and forth under light input, requiring a stronger, continuous push to complete the action. Avoidance (#1d) introduces evasive behaviors, such as rotation or retraction, preventing successful selection and emphasizing restricted actions. Privacy-#2 simulates a combination lock by requiring users to reproduce a demonstrated sequence of force-based gestures, combining nudges, presses, and shears at specific locations. Successful completion causes the pixel to rise through the surface, signaling unlocked access and readiness for further interaction.

5.3.3 Mindfulness. System-guided interactions to guide breathing and dialogic interactions to facilitate fidgeting. Mindfulness-#1 provides a physical breathing guide through slow vertical motion: the pixel rises over three seconds, pauses briefly, and then yields softly over four seconds, encouraging synchronized inhalation and exhalation. Mindfulness-#2 requires users to maintain gentle, continuous pressure on the pixel to keep the interaction active. When pressure is released, the interaction pauses, prompting refocus and re-engagement.

5.3.4 Physical Navigation. System-guided interactions that provide directional cues through force without relying on visual cues. Navigation-#1 delivers discrete directional cues through vertical pokes in one of eight compass directions. After a nudge of the pixel in the center, Navigation-#2 provides continuous guidance by sliding the pixel laterally under the user's hand towards the target direction, creating a sensation of being pulled. Similarly, after a user nudge, Navigation-#3 conveys turns through slight rotational twisting, mimicking steering; an extension introduces small bumps during twisting to represent dynamic obstacles or deviations from the intended path.

5.3.5 Notification Management. Dialogic and system-guided interactions focused on receiving, interpreting, and dismissing notifications through force. Notification-#1 communicates quantity and urgency through a force stack: incoming notifications increase the pixel's height and resistance. Notifications can be dismissed either incrementally, through a series of pushes corresponding to their number, or all at once by knocking the stack sideways. Notification-#2 uses vertical pulses as a baseline tactile signature to indicate multiple notifications over time. Notification types are differentiated through location-based cues and force patterns, combining variations in position, timing, and behavior (e.g. short pokes, slower pushes, or lateral oscillation). Notification-#3 extends this approach with expressive force messages—such as wave (#3a), orbit (#3b), zigzag (#3c), and fan-like (#3d) motions—enabling richer force-based communication.

5.4 Procedure

At the beginning of the study, participants were provided with an information sheet outlining the study's objectives. They had the opportunity to ask questions before providing informed consent to participate and providing basic demographic information. We then presented them with the five scenarios (in randomized order) using the Transforcer device. The scenarios were structured to investigate a mix of user-driven interactions (e.g. setting the time, fill out password, dismissing notifications), system-guided interactions (e.g. receiving force messages or navigation cues), and dialogic interactions (e.g. mindful fidgeting, negotiating selection). Participants were introduced and guided through each scenario, experiencing the Transforcer's force feedback and reflecting on how these haptic experiences conveyed information. For each scenario, context was provided, however interactions were not named or explained, but for the participant to figure out and explore. This was to understand how they intuitively approached each interaction. In case participants struggled with a task, the researcher would give incremental hints to guide them through (e.g. a hint for Time-based interactions was 'think about common ways you would set a timer').

The study used a semi-structured interview format to gather qualitative data from participants (see interview script in Appendix B). After each task, participants were asked how the different force modalities conveyed aspects relevant to the context of the scenario. Participants engaged in multiple scenarios, each followed by reflective questioning to probe their perceptions and the appropriateness of the haptic feedback used. This approach ensured that a wide range of contexts and force properties was explored. At the end of all scenarios, participants were given a sheet like that shown in Figure 5 that could be used to visually guide the post discussion. The entire study session lasted approximately one and a half hours and afterwards participants received £15 compensation for their time and effort.

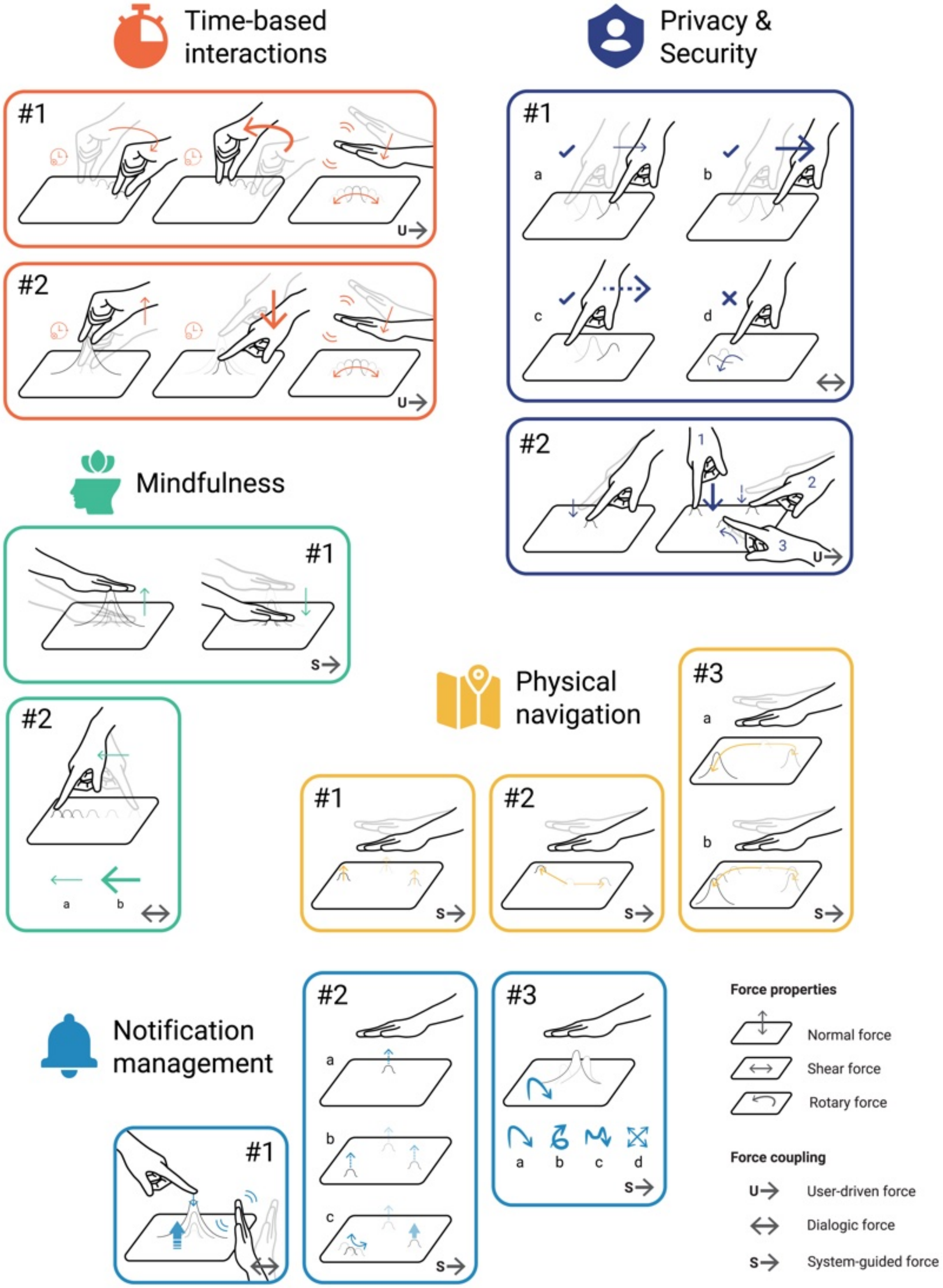

Figure 5: Overview of 5 scenarios: (i) Setting and adjusting time through user-driven shear rotary force (#1) or pull/push force (#2). (ii) Making privacy- and security-related selections through dialogic shear and push interactions (#1), or performing user-driven password unlocking through a sequence of pushes and shears (#2). (iii) Mindfulness interactions through system-guided normal-force breathing (#1) or dialogic shear-based fidgeting (#2). (iv) Receiving navigation cues through system-guided pokes (#1), slides (#2), or twists (#3) in the surface. (v) Handling notifications through diagolic normal and shear force interactions with a stack (#1), receiving system-guided force messages using normal force (#2), or combining force modalities for more intricate force messages (#3). See Appendix A for an enlarged overview.

5.5 Data Collection & Method of Analysis

Data collection involved audio- and video-recorded interviews, with participants' consent, to capture their reflections as well as hand movements and gestures when interacting with the device. The lead researcher transcribed all interviews.

The qualitative data from these interviews was analyzed using reflexive thematic analysis [6, 7] to identify patterns in how force-based interactions were appropriated and interpreted across different contexts. An initial inductive pass on a small subset of participants (2–3 per scenario) was used to gain an overview of the data across the five scenarios and to align both coders. Two researchers then split the dataset and each coded half of the interviews. They iteratively discussed and refined scenario-specific themes, which were later synthesized into the final set of five overarching themes.

6 Findings

Force feedback was understood through the body as a primary reference system, with participants using posture, (hand) orientation, gestures, and bodily awareness (e.g. breathing or subtle hand movements caused by the force) to make sense of the feedback. They treated force not as a neutral carrier, but as an expressive medium whose tactile qualities shaped both what actions felt possible and how meaning was constructed. Understanding emerged through a combination of immediate intuitions and evolving, personally learned mappings to familiar, metaphorical, or abstract concepts. Force interactions were experienced as relational and negotiated, with participants attributing varying degrees of agency, intent, and authority to the force pixel. Beyond information, force carried emotional and social tone, eliciting affective responses and social interpretations that went beyond what the force physically felt like. Participants evaluated force interaction in relation to everyday contexts, envisioning how it would be appropriated, constrained, or abandoned depending on situational demands. We elaborate on these findings through five themes: (i) embodied grounding, (ii) material expressiveness and sense-making, (iii) interaction dynamics, (iv) affective and social readings, and (v) contextual appropriation.

6.1 Embodied Grounding

Participants consistently interpreted force in relation to their own bodies. Meaning emerged through touch, posture, orientation, and bodily awareness, and participants often relied on bodily demonstrations to explain what the force 'meant'. In Mindfulness-#1, upward force was consistently mapped to inspiration and downward force to expiration, for example by comparing upward movement to increasing lung capacity (P7). Similar bodily anchoring appeared in Notification-#2, where participants mapped force to specific fingers or hand postures, such as assigning apps to individual fingers (P2: *"I want my index finger to be Instagram, thumb ... Outlook"*). Across scenarios, participants used their bodies to anchor, decode, and communicate the meaning of force feedback.

Further, this bodily grounding was scenario- or person-specific rather than universal. Participants drew on personal habits, cultural metaphors, and task demands to make sense of where and how force was applied. For instance in Navigation-#1, P10 interpreted a localized force on the palm as marking a specific location, treating their hand as a spatial map. This mapping relied on a culturally learned bodily metaphor that would not be available to all participants: *"I'm from Michigan (US) originally, which as a state is shaped like a mitten. A traditional thing that we do is you will show people your hand, and be like 'I'm from here [points to palm]."*

Force sometimes drew participants inward, towards bodily awareness (e.g. Mindfulness-#1), while in other cases it pulled attention outward toward controlling or negotiating with the device (Mindfulness-#2). When these orientations conflicted, participants reported frustration or confusion. As explained by P4: *"I do this thing called pressure points, where you tap different parts of your body as a grounding technique. This [pixel] could be a way to have that be purely about the sensation, without having to worry about, where do I tap my pressure points? You can pop your palm down and the machine starts interacting with your hand. Feeling force and pressure and physical sensations on the body is already extremely mindful anyways, it's an embodying experience"*. When force required active control without offering a clear bodily reference, attention shifted away from grounding and toward frustration: *"I have to concentrate quite a lot, to get it [pixel] to do what I want it to do. I guess that keeps my mind off other things, but mostly annoyed that it's not quite doing what I want it to do"* (P11). So, the effect of force depends on whether bodily attention and system behavior align.

Participants reflected on the necessity to make force interactions suited to their body, in terms of hand size, strength, and movement patterns. Both from an accessibility standpoint, as well as a meaningful resource, particularly in security contexts. In Security-#2 this was framed as a benefit: personalized gestures and force signatures were seen as more secure because they are tied to individual motor capabilities and mannerisms. However, whereas personalization could increase security, it could also tie interaction success to physical capability: *"If I'm very skilled and I'm able to precisely relay the same force pattern and position, then I've probably created a very secure password. But if I'm not very good at that, dexterously, then I'll probably create one that's very easy in terms of thresholds [...] Then that maybe relates to a less secure password. Unfortunately, then you tie physical capabilities of the user to password security, which is maybe not accessible to lots of people, is potentially an issue"* (P4). So embodied grounding enables rich, personalized meaning-making, but it also embeds assumptions about bodies that cannot be taken as neutral.

Taken together, these findings show that bodily grounding enables force interaction to make sense—but only as long as bodily reference, task demands, and system behavior remain aligned. This was especially apparent in the scenarios Mindfulness and Navigation, where participants relied most directly on bodily awareness and spatial body mapping to interpret and engage with force.

6.2 Material Expressiveness & Sense-making

Force interactions were not interpreted through material qualities alone, but through participants' active sense-making processes. While properties such as resistance, directionality, and duration shaped what actions felt possible, meaning emerged as participants mapped these sensations to familiar concepts, practices, and expectations. Material expressiveness and semantic interpretation were therefore tightly intertwined: force became meaningful through how it constrained action, evoked references, and aligned with task and context.

Participants consistently interpreted force output as communicating what actions were allowed, encouraged, or blocked. In Security-#1, resistance clearly signaled invalid actions, as P1 noted: *"it's telling me, I can't do that [...] you have to go that way"*. Here, meaning was inferred directly from how force responded to bodily input, grounding interpretation in immediate physical feedback rather than abstract concepts. Similar reasoning appeared in Time-#2, where several participants adopted an upward 'pumping' gesture using a repeated beckoning-like motion of the index finger, and interpreted the resulting increase in height as a direct, one-to-one mapping between action and system response. Although the interaction also allowed continuous input, this more incremental enactment was described as easier to understand than the continuous rotation used in Time-#1. Across scenarios, duration and effort of force further shaped perceived possibilities: sustained input force was often associated with confirmation or commitment, while brief or fleeting output force suggested guidance or nudging. Participants further reasoned about force using spatial (e.g. up/down), directional (e.g. clockwise/counterclockwise), and quantitative structures (e.g. more pull meaning more time, or resistance signaling an invalid action) that helped turn physical sensation into actionable information. Across scenarios, one-to-one mappings, where a single action corresponded clearly to a system response, were particularly valued.

To make sense of force interactions, participants frequently relied on familiar mechanical references, contemporary digital experiences, and metaphors from nature. Mechanical metaphors, such as dials, switches, or joysticks, provided immediate expectations about range, limits, and the nature of the action, especially in more pragmatic scenarios like Time and Security. For example, P11 compared Security-#1a to *"old knife switches"*, describing how the required effort conveyed importance and danger. Digital references could also help decipher actions, especially when force movements resembled contemporary touch interactions, such as Notification-#1 reminding participants of swiping away notifications. Natural references were sometimes preferred, as with Time-#2: *"a clock face is a ridiculous human construct, whereas sand seeping away is a representation of time that is more associated with the tides, nature, and gravity"* (P5). Force behaviors without clear analogue were described as *"alien"* or harder to grasp, drawing attention back to the device itself rather than the task.

While similar force qualities appeared across scenarios, their meanings shifted with context. To give some examples, in Security, resistance and required effort were interpreted as seriousness, intentionality, and safety, with force contributing to a sense of control rather than a hindrance. As P4 explained, *"I'm associating force with seriousness [...] like big clunking mechanisms in a safe"*. In Mindfulness-#2, resistance was variably experienced as grounding, calming, or frustrating, depending on whether it supported flow or hindered fluid movement; P9 described it as *"dragging a stick through sand"*. In Navigation, short upward pulses (#1) conveyed certainty and clear direction, whereas slower or continuous movements (#2 – #3) were read as tentative guidance or gradual orientation. The 'bumps' in Navigation-#3b were associated with a car indicator (P2), turn increments in a compass (P5), reaching destination (P1), terrain texture (P4), and number of degrees or times to direction (P9). In Notification-#2c, slow continuous upward force suggested an incoming call, whereas lateral force was interpreted as the call ending (P1) or being on silent (P2); spatial multiplicity conveyed multiple entities or a conversation. Across scenarios, similar force profiles could convey different meanings, and participants often interpreted forces uniquely based on their own prior experiences and conceptual framing.

Material expressiveness broke down when force feedback lacked sufficient resolution, granularity, or internal consistency. In Time Management, participants struggled to achieve precision through continuous force alone, describing a tension between immediacy and accuracy. Similarly, coarse or discrete force positions reduced trust in Security-#2, as P12 explained that discrete positions felt less secure than continuous, signature-like input. When force cues were ambiguous or hard to differentiate (e.g. Security-#1d), participants expressed confusion and reduced confidence, and difficulty interpreting or trusting the interaction.

Participants also reflected on force as a learnable interaction language. Some mappings felt immediately self-revealing, while others required exploration and repetition. Familiarity reduced cognitive effort, whereas unclear mappings prompted reflection on how interactions might evolve over time, much like swiping, scrolling, or rotary dialing. P6 highlighted this generational dimension: *"if you show a rotary phone to a teenager, they will push the buttons because they've only ever seen 'button push'; the idea of sliding motion doesn't appear to them. For my grandparents, if you show them a smartphone, they want that tactile feel that they are actively activating something"*. Several participants noted that what feels 'intuitive' depends on generational and cultural experience, suggesting that force-based interactions are not universally legible but become meaningful through exposure, practice, and shared conventions.

This theme was particularly visible in Time and Security, where force was often interpreted through familiar mechanical or procedural metaphors, but also in Navigation and Notification, where similar force qualities took on different meanings depending on context. Rather than carrying fixed semantics, force became meaningful through how its behavior aligned with the situation at hand.

6.3 Agency & Interaction Dynamics

This theme focuses on the relationship between the user and the pixel, emphasizing how participants experienced control, negotiation, and dialogue during interactions. Across scenarios, the pixel was rarely treated as a passive output channel. Instead, participants described the interaction as a negotiated relationship, where control shifted between themselves and the pixel. The pixel could guide, resist, respond, collaborate, demand attention, or act with a sense of agency, creating a dynamic interplay of perceived intent and user action.

Participants often relied on familiar interaction patterns to assert control. In Navigation-#2 and #3, for example, participants appreciated being able to initiate feedback rather than having the system act autonomously. P4 noted, *"I like the agency because I'm the one that's initiating this; 'I need help, come on nubbin' ... 'tell me which way to go?'"* Similarly, P1 highlighted the intuitiveness of self-initiated interaction: *"I do really like being able to ask it, to input* *something into it, and then get that feedback"*. P11 reflected on the subtlety afforded by user control: *"It's nice that it's user controlled. It's not too intrusive, because it's only telling you directions when you want them"*. Here, control was empowering, participants could act effectively, and the interaction felt collaborative instead of directive.

However, when system behavior was unpredictable or ambiguous, agency collapsed into frustration or antagonism. For instance, in Mindfulness-#2, participants struggled to predict the pixel's responses. P10 remarked, *"I don't have quite as much control as I'd like, that's where I think the biggest issue is"*, while P1 observed, *"if I knew that's the path it was on [...] then maybe it would have felt a bit nicer"*. The same ambiguity could also be enjoyable: P7 described it as *"not necessarily obvious what I'm meant to be doing [...] but it's quite enjoyable. It's a nice fidget"* and P4 reflected,*"it's making me frustrated, but it's maybe teaching me to be accepting of it"*. In these cases, participants' sense of control was partial, and the pixel's unpredictability allowed for exploration, play, or reflective engagement with the interface.

In some scenarios, control was shared more explicitly between user and system. For example, in Security-#1b, P6 described the interaction as *"more interactive, like you're working together to achieve something, rather than the device actively preventing you from something. [...] This is more, you're petting it, and it's going, 'Okay, I'm letting you do that to me'"*, framing the pixel as a collaborative partner rather than an obstacle. P12 similarly envisioned for Security-#2, *"if it's more like holding a pen and writing [...] and it feels more like a joystick that doesn't physically push back"* that it would feel more useful and cooperative, highlighting how subtle responsiveness would increase perceived agency.

Perceived pixel autonomy also influenced participants' sense of agency. In Security-#1, force feedback sometimes conveyed the system's resistance to participant actions; P4 recalled that when the pixel nudged their finger (#1b), *"it was like, 'no, don't do it'"*, framing the pixel as an agent not wanting them to make a decision. In Mindfulness-#1, participants experienced the pixel as both guiding and imposing. P6 explained, *"if you're trying to force a behavior from a user, like, breathe [...] this would be quite nice, because it sort of says, 'in, hold it to this point, and out'"*, whereas it could also conflict with autonomy and mindfulness *"the fact that it decides how high it goes, the force it applies to you, is less pleasant because ... you have to just obey it"*. In Mindfulness-#2, participants imagined the pixel as a little creature exploring a maze, P9 described: *"it feels like you're exploring around a little maze or something, giving a little creature a nudge, and it's going off doing its own thing"*. In these examples, participants attributed intentionality and personality to the pixel, blending physical force with emotional interpretation.

Overall, the sense of agency in interactions depended on the alignment between participant expectations, the pixel's responsiveness, and familiar interaction patterns. When control was predictable or self-initiated, interactions were empowering and enjoyable; when ambiguous or inconsistent, they could feel frustrating, confusing, or playful. Experiences of agency were most pronounced in Navigation, Mindfulness, and Security, where participants alternated between initiating, following, resisting, or negotiating with the pixel. This dynamic highlighted the importance of balancing autonomy, responsiveness, and legibility, so that the pixel's perceived 'agency' supports rather than hinders interaction.

6.4 Affective & Social Readings

This theme focuses on how force was also read as socially and emotionally expressive, raising questions of agency: whether force was experienced as something the pixel did, or as something done through the pixel by another person. This was especially apparent in Notification Management, where force was frequently understood as a socially expressive act with an implied sender, intent, and tone.

Across scenarios, participants described force feedback using emotionally and socially charged language. Rather than focusing on what the force represented in an informative way, they spoke about how it felt to receive it: as playful, irritating, caring, unsettling, or intrusive. In Notification Management, force was often interpreted as carrying an emotional undertone similar to a message or gesture from another person. For instance, the repeated and protruding force in Notification-#1 was compared to someone persistently trying to get attention: *"It feels a bit like, 'hey! hey! hey!' [...] like 'you ignored me once, let me try again'. Because it's getting more pronounced and obvious"* (P10). In contrast, softer or more exploratory motions such as Notification-#3b were read as gentler social approaches: *"It's like a gentle kind of, hello. The movement isn't so direct, it's kind of curved, a bit more exploratory"* (P1).

The same force patterns could elicit very different emotional responses depending on their material qualities. Pace, pressure, repetition, and trajectory shaped how intent was perceived. Jittery or sharp motions (e.g. Notification-#3a, Navigation-#3b) were described as irritated or demanding, while smooth, curved, or lighter movements (e.g. slow lateral motion in Notification-#2c, Notification-#3b & #3d) were often framed as friendly or playful. However, similar motions could be described varied by different participants, for instance, P1 compared the slow flowing motion of Notification-#3d to sending a GIF or emoji, *"it's just a fun little movement, a fun little thing that I'm sending you"*, whereas P8 had a more negative perception of that same motion: *"I don't think, I'd be pleased to read this message [laughs]. It feels like, there is some sharpness in the message, someone complaining about something"*.

Interestingly, force interactions often took on a social tone even when no explicit social meaning was intended. Participants frequently described force as resembling touch, such as stroking, tapping, or poking, which introduced questions of intimacy and appropriateness. In some cases, this led to discomfort or rejection. A slow, repetitive lateral motion across the thumb (within Notification-#2c) was described as *"creepy"* and seen as an unwanted touch: *"You're like, 'nope, no, please don't touch me like that'"* (P10). Another participant remarked that while such a gesture can communicate tenderness or affection, *"you'd definitely don't want it from your boss [laughs]"* (P12).

These reactions illustrate how intimacy can emerge unintentionally through force feedback. Even when participants recognized that the motion was generated by a device, they still imagined a sender behind it, and evaluated the interaction accordingly. The acceptability of force therefore depended not only on its physical characteristics, but also on who it was imagined to come from. Some participants explicitly differentiated between force as a prerecorded system behavior and force that might be directly enacted by another person. P11 noted that a gesture might feel more acceptable if it were clearly and immediately performed by someone else, rather than designed by an anonymous company: *"This feels like a pre-recorded stroke [...] it's some tech bro in Silicon Valley who's designed this thing, and it's stroking me. That's weird"*. At the same time, participants also identified playful and enjoyable aspects of force interactions, such as sending particular force patterns to friends. P10 suggested deliberately sending and unsettling motion to friends as a joke, acknowledging both its creepiness and humor. These responses suggest that force feedback can support a vocabulary of social and emotional expression, but that this is highly context-dependent and sensitive to tone, relation, and expectation.

Overall, this theme shows that force feedback is not only interpreted through bodily or conceptual mappings, but also through affective and social readings. Especially in the Notification Management scenario, participants treated force as a form of touch-like communication, where imagined intent and sender mattered as much as the signal itself.

6.5 Contextual Adaptation & Appropriation

This theme captures how force-based interactions fit into everyday contexts and how participants learned, adapted, and appropriated it over time. Participants reflected on how force compares to visual, auditory, and vibrotactile feedback, how it supports different forms of interaction, and how its suitability depends on context, application, and integration.

Participants often described force as more visceral, immediate, and memorable than visual or auditory feedback, particularly when other senses were already occupied or when social discretion mattered. Force was frequently characterized as harder to ignore, eliciting an embodied response rather than requiring deliberate cognitive processing. As P8 explained, haptic sensation prompted an immediate bodily reaction that *"felt like something I should pay attention to"*, whereas visual information could be more easily filtered or ignored. At the same time, participants emphasized that this attention-demanding quality made force both more discrete and more intrusive, depending on context. Compared to a short *"ding"* or *"buzz"*, force feedback involved *"more going on"* and could feel less subtle (P9). Additionally, participants noted that force requires intentional touch to be perceived, which limits its usefulness in situations where hands are already busy.

As participants became familiar with the system, they moved beyond single-finger tapping and appropriated force through a range of bodily interactions, including pinching, grabbing, placing the palm to 'listen', and engaging both hands. These interaction styles emerged gradually and were shaped by how force was embedded in the surface. P6 described how concealing the actuated pixel invited them to shift from cautious fingertip exploration to more whole-hand engagement: *"with the previous one [task] I was trying to go at it with one finger, and now I'm like, 'I'm going to use more of my hand, I'm gonna grab it'. I think by trying to hide it [pixel] in there, it's sort of inviting you to come with it"*. Participants also emphasized that force-based interaction felt more consequential than tapping, as physical interference could directly interrupt or resist system behavior. P4 described this as a clear sense of cause and effect: *"the comparison would be, somebody's heart beats on the screen and I just touched the screen, that's inconsequential. Whereas this has consequence, I grabbed it and it stopped. [...] Or sometimes when my hand was in the way, it [pixel] would stop, and I would lift my hand, and it would carry on"*. Beyond confirmation, force was also seen as a way to guide interaction, for example steering the thumb towards a target rather than just signaling success or failure.

Participants consistently identified Navigation and Mindfulness as particularly suitable applications for force-based interaction, often describing them as more embodied or physical activities. In these contexts, force supported eyes-free interaction and reduced reliance on visual or auditory attention, for example by subtly guiding direction without requiring users to look at a screen. One participant noted that this could help avoid becoming a *"phone zombie"* while walking (P9). Force was also seen as potentially valuable in safety-critical, high-noise, or low-visibility environments. At the same time, participants emphasized that not all tasks benefited equally from force. Activities such as time tracking were described as remaining visually dominated, and some participants raised concerns around accessibility and tactile skill in security contexts, as well as the social implications of force-based notifications.

Envisioning beyond the study scenarios, participants emphasized that force-based interaction works best when tightly integrated into specific contexts rather than applied generically. Tailored integration into tools or devices already held—such as steering wheel, gloves, or controllers—was described as more convincing and useful than force added to a general-purpose smartphone (P12). Personalization was described as important as well, particularly in relation to hand size, finger strength, and force thresholds. Participants emphasized that successful adoption of force-based interaction depends on how intuitively it can be learned and appropriated across different users, contexts, and abilities. For instance, P7 proposed starting with a small, localized force-based element, such as a bottom bar on a phone, to support everyday trial and learning without overwhelming users. More broadly, participants reflected on force as a fundamentally different communication channel from visual or auditory modalities: *"We communicate through visual drawings, written language, or auditory information. [...] But we don't really communicate through touch on that general scale, we navigate the world through touch. [...] So to receive it, it would be a new language. So they'd really have to be intuitive, and you'd have to align it with that sort of library of information"* (P3). While participants saw force as a rich and expressive interaction channel, they also described it as introducing a 'new language' of touch that requires careful design to feel intuitive and safe, especially when force can physically override user intent and when accounting for differences across cultures, generations, and abilities.

This theme of contextual fit surfaced most clearly in Navigation and Mindfulness, which participants often described as particularly compatible with force-based interaction, but was also evident in Time, Security, and Notification, where the limits of force became more visible. Together, these scenarios show that the value of force depends not only on what it can express, but on when, where, and for whom it is introduced.

6.6 Summary

Across embodied grounding, material expressiveness, mapping and sense-making, and interaction dynamics, participants engaged most effectively with force feedback when bodily, material, and conceptual reference points aligned. Force made sense not because any single layer was intuitive on its own, but because these layers reinforced each other, through a delicate balance of bodily intuition, material response, and conceptual expectations. Misalignment, ambiguity, or contradiction between layers could reduce interpretability, requiring participants to negotiate meaning actively rather than passively perceive it. Bodily grounding provides a foundation, but meaning can fall if expectations are unmet; material expressiveness constrains action but does not guarantee understanding; conceptual mappings are constructed through use, yet remain highly individual and task-dependent. Social and contextual factors further shape this experience, highlighting that force interaction is a multi-layered process, shaped by context, prior experience, and bodily capability.

7 Discussion

Here we discuss how surface-based force interactions are interpreted and appropriated by users, addressing the research question: *How can the affordances and cues of everyday tangible interactions inform the design of surface-based force interactions?* We position surface-based force not as a universal input-output mechanism, but as a consequential, learnable, and context-sensitive interaction modality which meaning emerges through bodily engagement, contextual grounding, and social interpretation. Drawing on our findings, we synthesize conceptual insights and design implications that focus on interpretation and appropriation of force interactions, and articulate what this implies for future design and research.

7.1 Force as a Multi-layered, Consequential Modality

Our findings suggest that surface-based force interactions are inherently multi-layered and consequential. Unlike visual or auditory feedback, force is experienced through bodily sensation and physical consequence, making interpretation inseparable from action. While this study deliberately focused on force in isolation—minimizing auditory and visual feedback to allow close attention to force-based interaction—our findings nonetheless reveal how force is interpreted through multiple, interdependent layers. Bodily sensation, material behavior, conceptual mapping, and context were inseparable in participants' interpretations, even when force was the primary feedback channel. This suggests that surface-based force interaction design is difficult to understand as a single-modality problem. Rather, the multi-layered relations observed here point towards future opportunities to explore multisensory or multidirectional interaction approaches, in which force is intentionally coordinated with touch, sound, vision, and proprioceptive cues.

Prior work has emphasized the layered nature of haptic experiences. For instance, Dalsgaard et al. [10]'s Inference-Design Model describes how haptic interaction unfolds through layered inferences across sensation, interpretation, and meaning-making. Our findings resonate strongly with this view, while extending it by showing how surface-based force introduces a particularly consequential form of inference: users not only interpret force but must physically negotiate with it, making misalignments between layers immediately felt and difficult to ignore.

7.2 Personalization and Context-Dependence

While our Transforcer device was intentionally exploratory and constrained—featuring a single force pixel and a relatively bulky form factor—these limitations helped surface important insights about personalization and context-dependence. For instance, participants' interactions were shaped by hand size, strength, and how the force pixel related spatially to their grip or posture. Systems such as DeFormIO [30] and HydroHaptics [29] demonstrate how force and deformation can be embedded across diverse form factors, including smartphones, interactive displays, controllers, wearables, and soft objects. While these works focus primarily on technical expressivity and integration, our study complements them by foregrounding how users interpret and appropriate force in situ, highlighting the importance of tailoring not only form factor but also force qualities, mappings, and social meaning.

7.3 Learning, Mapping, and Interpretive Variability

Our findings indicate that force interaction knowledge emerged through exploration. Participants learned how to interpret and engage with force through repeated interaction, experimentation, and adjustment, and mapped these sensations to familiar concepts. In this sense, force appeared to function as a learnable and negotiable interaction language, with meaning taking shape through use and interaction over time.

This emphasis on exploration resonates with recent works such as Shape-Kit [57] which explicitly addresses the gap between the exploratory nature of haptic design and challenges of technical reproducibility. By providing modular building blocks for force and shape actuation, Shape-Kit enables designers and researchers to iteratively explore mappings, body locations, and interaction qualities through hands-on experimentation. Our findings similarly suggest that supporting iterative exploration is essential for meaningful force interaction design, given the absence of a single, universally intuitive mapping between force and digital concepts.

Participants' interpretations also revealed the variety of distance that can exist between force quality and their conceptual mappings. Familiar references could come from a variety of sources, such as mechanical, contemporary digital, or natural concepts, which would provide some recognition and introduce pre-emptive expectations. However, then connecting these to the interaction context introduced an additional interpretive layer. When this connection was ambiguous or misaligned, participants expressed confusion or frustration, highlighting how breakdowns in mapping can disrupt learning and sense-making.

While our findings highlight strong person-specific interpretations of force, future work could investigate which force cues might be generalized across users. Identifying common perceptual patterns or shared mappings could help establish a more standardized vocabulary for surface-based force, supporting design guidelines that balance personalization with broader applicability.

7.4 Affective and Social Affordances of Force

Prior work has argued that touch coming from haptic devices can be experienced as inappropriate or intrusive [22]. Our findings reinforce this concern, while also illustrating how force can convey affective and social meaning when carefully situated. Participants were highly sensitive to subtle force qualities—such as jitteriness or smoothness—which were interpreted as emotional or social cues rather than purely mechanical artifacts. As Jewitt et al. [22] argue, designing 'touch technologies' requires democratized exploration and innovation than replication of existing (digital) touch practices. Our work aligns with this stance, suggesting that force-based interactions need to not rely on one-to-one mappings and existing structures, but can instead support personalized and culturally situated forms of feedback.

7.5 Takeaways for Designing Surface-Based Force Interactions

Surface-based force interactions are inherently multi-layered, integrating bodily, material, conceptual, and social dimensions. Designing for this modality therefore requires a holistic approach rather than one-size-fits-all solutions. Toolkits such as Shape-Kit [57] lower barriers to exploratory haptic design by enabling modular experimentation with force and developments such as HydroHaptics [29] illustrate how high resolution deformable force interactions can augment existing systems. Importantly, surface-based force shows particular advantages in tasks with strong physical or embodied components, in safety-critical situations, or when conventional sensory channels are limited. Based on our findings, we highlight several guiding considerations:

1. **Interpret force holistically across layers**: Force is interpreted simultaneously through the body, material qualities, conceptual mappings, and within context. Misalignment between these layers can reduce interpretability or engagement, while alignment can make interactions intuitive and meaningful. For example, a smooth resistant push on a navigation interface can clearly indicate direction or boundary.
2. **Personalize physical and conceptual experience**: Users differ in hand size, strength, dexterity, and how they perceive concepts such as urgency, importance, or social tone. Tailoring force feedback to both physical capability (e.g. finger vs. palm) and interpretive experience (e.g. gentle vs. demanding force) enhances usability.
3. **Context and device matter**: Force works best when integrated into specific contexts or tools—such as gloves, steering wheels, or controllers—rather than applied generically across devices. Tasks with strong physical or embodied components (e.g. navigation, mindfulness) likely benefit most from force, while digitally oriented or visually dominated tasks (e.g. time tracking) are often better served by traditional modalities.
4. **Support learning through familiar metaphors and exploration**: Force mappings are not universally intuitive, so familiar mechanical, digital, or natural analogies (e.g. dial resistance, swiping motions, sand seeping away) can help users interpret force, while iterative exploration—such as pinching, grabbing, or engaging multiple fingers—allows them to appropriate this tactile language over time. Gradual introduction supports learning across generational and cultural differences.
5. **Account for agency and control**: Force is inherently bidirectional and consequential: physical interference can interrupt or resist system behavior, creating a clear sense of cause-and-effect. Misalignment between user intent and system response can cause frustration, while predictable, user-initiated interactions foster engagement. This is particularly relevant in navigation or security-critical tasks.
6. **Harness affective and social meaning deliberately**: Force can carry emotional and social cues. Smooth, slow motions were often perceived as calm or friendly, while jittery, abrupt motions felt agitated or demanding. These cues can enrich digital communication, such as messaging or video calls, but interpretation depends heavily on context and relationship.
7. **Use force judiciously**: Force is attention-demanding and physically consequential. It is most effective in scenarios where it adds clear value, such as safety-critical operations, low-vision interaction, or contexts where sound would be inappropriate. Continuous or generic application can potentially feel intrusive or fatiguing.

7.6 Limitations and Future Work

Our prototype and study were constrained in several ways. First, the Transforcer features a single force pixel in a relatively bulky form factor, unlike personal devices such as phones or tablets. While this allowed us to explore force interactions in isolation and without constraints from existing form factors, it limits generalizability to multi-pixel or compact interfaces. Future work would be required to investigate how multiple force pixels can cooperate to create richer haptic experiences. The study also focused primarily on force feedback, minimizing complementary auditory and visual cues; exploring multisensory integration could reveal how surface-based force interacts with other modalities in interactive systems.

Second, our empirical exploration covered only a subset of the proposed design space. The prototype and study allowed us to solely investigate the dimensions of Force Properties and Force Coupling. This scoping was intentional, allowing us to focus on the mechanics and dynamics of force in a device-agnostic and exploratory way, but it also limits how broadly the findings can be generalized across possible instantiations of force-based interfaces.

Third, participants were recruited based on their expertise in HCI and interactive systems to support reflective engagement with unfamiliar force interactions. While appropriate for this exploratory study, this may also have shaped the findings towards more speculative or design-oriented perspectives and may not fully reflect how non-expert or everyday users would experience and interpret such interactions. Future work should therefore examine surface-based force interactions with broader participant groups and in more situated contexts of use.

Finally, the prototype was limited in the range and tuning of force output, including depth, strength, and subtlety of movement, which may have influenced participants' interpretations and use. Future work should explore higher-resolution actuation to further develop and extend the design space of surface-based force interactions.

8 Conclusion

This paper explored how the affordances and cues of everyday tangible interactions can inform the design of surface-based force interactions. This provides the first step towards a holistic understanding of how users perceive and interpret force input and output, and how these perceptions shape interactions with force-based devices. We introduced the Force Pixel design space, which conceptualizes the smallest unit of force interaction and grounds design in the physical properties of mechanical force and how it is interpreted by users. Building on this framework, we developed the Transforcer device, capable of generating normal, shear, and rotary forces to support user-driven, system-guided, and dialogic force interactions. Through semi-structured interviews across five experiential scenarios, we found that force is interpreted through multiple interdependent layers—bodily sensation, material behavior, conceptual mapping, and (social) context—and that meaning emerges through exploration and negotiation. Based on these insights, we proposed design takeaways emphasizing how force feedback is most effective when holistic, personalized, and contextually grounded. While not universally applicable, it provides a unique channel to enhance digital interactions with tangible, bodily, and socially meaningful experiences. Our Force Pixel design space and scenarios illustrate the potential of this modality and serve as a foundation for future investigations in designing surface-based force interactions. Ultimately, surface-based force interactions open up new possibilities for designing interfaces where meaning emerges through active physical negotiation, creating rich, embodied, and socially nuanced experiences that go beyond conventional input-output paradigms.

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