Body-Centric NFC: Body-Centric Interaction with NFC Devices Through Near-Field Enabled Clothing

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ABSTRACT

NFC (Near-Field Communication) has been widely applied for human-computer interaction (HCI). However, the short sensing distance of NFC requires the users to initiate the tasks with extra effort mostly using their hands, so it is inconvenient to use NFC in hands-busy scenarios. This paper presents an investigation of body-centric interactions between the NFC device users and their surroundings. The exploration is based on the recent development of near-field enabled clothing, which can passively extend an NFC-enabled device's reading distance to users' body landmarks. We present an accessible method for fabricating flexible, extensible, and scalable NFC extenders on clothing pieces, and an easy-to-use toolkit for facilitating designers to realize the interactive experiences. The method and toolkit were tested in technical experiments and in a co-creation workshop. The elicited design outcomes and the further exploratory makings generated knowledge for future research and embodied interaction design opportunities.

CCS CONCEPTS

• **Human-centered computing → User interface toolkits**; **Ubiquitous and mobile computing systems and tools**; **Interaction design theory, concepts and paradigms**.

KEYWORDS

Embodied interaction, body-centric interaction, near-field enabled clothing, wearables, near-field communication, NFC.

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Figure 1: Body-centric interaction with NFC devices through a piece of near-field enabled clothing, which extends the reading range of a mobile device's NFC to the user's protruding body landmarks (e.g., elbows) for touch interaction.

1 INTRODUCTION

In tangible and social computing systems, embodied interaction [14] leverages the user engagement directed toward the tasks in the real world, so the users can better exploit their existing knowledge of the physical world as well as their bodily, social, and environmental awareness and skills [31]. Based on embodied interaction, body-centric interaction [49] aims to further exploit the benefit made available by the body, including the users' sense of proprioception that allows some operations to be performed *eyes-freely* and the direct use of body cues such as facial expression and posture to help manage interpersonal social coordination. These interaction schemes laid important foundations for today's human-computer interaction (HCI) designs in mobile and ubiquitous computing [55].

NFC (Near-Field Communication) technology is equipped with current mobile devices (e.g., smartphones and smartwatches) to provide a reliable channel for bi-directional data communication between battery-less devices (e.g. tags, sensors). Although NFC has been widely applied as a user interface for tangible and social computing systems, the short sensing distance (i.e., up to 10cm) requires users to initiate the tasks by making extra efforts to overcome the distance, for instance, through actions such as pulling their phone out of a bag to read the tag. Researchers have proposed wearing NFC readers (e.g., [4, 17, 38]) to enable embodied and body-centric interaction in the context, but the corresponding hardware deployment and maintenance compromise user-friendliness.

To reduce the active electronic components and the accompanying maintenance, Lin et al. [39] recently proposed a system of *near-field enabled clothing*. Near-field enabled clothing is a passive garment with a network of textile NFC extenders, namely *near-field relays*, sewn in a star topology as a body-area network. The network extends the reach of an NFC-enabled smartphone (or any NFC reader/writer) placed at the hub of the network to the users' multiple body parts, allowing for power supplies and data communications between the phone and multiple batteryless sensor devices deployed on the garment or the user's body simultaneously. However, these near-field enabled clothing pieces were mainly proposed for body-area networking rather than an interface for embodied and body-centric HCI. It is also unclear how to customize and fabricate these clothing to fit the dimensions of the bodies [51] of different users to facilitate individual needs in embodied and body-centric HCI.

Therefore, in this paper, we present an investigation of body-centric interaction with NFC devices through near-field enabled clothing, namely *Body-Centric NFC*. We aim to systematically explore the embodied, body-centric HCI aspects and the applications for the NFC device users to interact with other individuals, objects, and environments [7].

Figure 1 illustrates a plausible scenario for Body-Centric NFC. Lisa wears a jacket that extends her NFC-enabled smartphone from the pocket to her elbows. After checking out from the supermarket's counter with two handfuls of shopping bags, she collected the coupons on the wall with her elbow. After ten minutes of driving, she arrives at the gate of her apartment and says, *"phone, use my access card"* and then bumps her elbow to the access-control device to get herself in. After she heard a beep sound, the door opened and she met her new neighbor Mark, noticed that he is wearing the same type of jacket, and she says, *"hey, we should hang out sometimes."* Then, Mark and Lisa bump their elbows to exchange the contact information. *"See you soon!"* they said to each other.

The scenario highlights that the limited availability of mobile phones usually occurs when the users' hands are busy or when direct touch interaction is considered unhygienic (e.g., during the epidemic). Although wearing a watch may mitigate the problem, the access point is still limited. By wearing a piece of near-field enable clothing that extends the reading range of an NFC device to the user's multiple protruding body landmarks (e.g., elbows), which provides physical affordance for hands-free touch interaction [20, 54], practical tasks can be accomplished in a natural way.

We explore the design space in a research-through-design [58] method. After we reviewed the related work, theories, and state-of-the-art, we first exemplified body-centric interaction with NFC devices based on the existing theories and technical capacities and formulated design guidelines. With the guidelines, we explored ways to leverage rapid prototyping techniques (e.g., vinyl-cutting circuitry) to implement near-field relays as design tools, examine the design guidelines and their performance through technical evaluation, and use them to realize a reliable proof-of-concept garment that provides a concrete embodiment of theory and technical opportunities. With the tools and artifacts, designers embodied the application scenarios and elicited early user experiences through a co-creation workshop and exploratory making activities. The encouraging user feedback and design outcomes highlight potential applications of the body-centric NFC interaction techniques and demonstrate the preferred states [58]. Finally, we reflect on the knowledge generated from the design research process and outcomes and elucidate plausible future research directions.

The main contributions of this work are 1) an accessible method to design and fabricate on-body NFC extenders which are also validated by two technical experiments and a proof-of-concept demonstrator, 2) a toolkit that has been tested in a co-creation workshop with practitioners, and 3) a series of exploratory makings that extends the repertoire of embodied interaction design.

2 RELATED WORK

2.1 Embodied and Body-Centric Interaction

Embodied interaction is the *"creation, manipulation, and sharing of meaning through engaged interaction with artifacts [14]"* that was coined by Dourish as a fundamental and unifying principle for designing interactive systems for tangible computing and social computing. An embodied interaction system leverages the user engagement directed toward the accomplishment of practical tasks by moving its design towards a better fit with everyday human activity, understanding, and interaction in physical and social reality. Such a system is interpreted by the users as *ready-to-hand* [26], which allows them to act *through* it and make it meaningful in the real world. If the users focus on interacting with the physical objects or humans, they can better exploit their existing knowledge of the physical world and their body, social, and environmental awareness, and skills [31]. Klemmer, Hartmann, and Takayama [34] also synthesize themes, such as learning and social collaborations that are salient for interaction design that involves human bodies and argues that realizing them in the real world rather than in a simulated, virtual reality is a more prudent path because *"a real-world interface can obviate many of the difficulties of attempting to model all of the salient characteristics of a work process as practiced."*

Based on the aforementioned theories, Shoemaker et al. [49] proposed a body-centric interaction model intending to capture the benefit made available by the body. The key benefits include the users' sense of proprioception that allows some operations to be performed *eyes-freely* in the user's personal space without reliance on the visual feedback provided by a display and the direct use of body cues such as facial expression and posture to help manage interpersonal social coordination. This model has inspired HCI researchers to exploit the benefits of body-centric interaction, such as extending the interaction space of a mobile device [6, 36] or providing on-body UIs that leverage the body skin [25, 40], body landmark [23, 54], muscle activation [50], body coordinate [22], and hand gestures [2, 10] for HCI.

2.2 NFC for HCI

NFC is a subset of radio frequency identification technologies (RFID) that operates in the same frequency range as high-frequency RFID. NFC supports the quick exchange of information between devices or tags in close proximity. With an NFC tag attached to the surface, a touch on an everyday object can be identified by the reader. The nearness (< 5-10 cm) of NFC provides the context [13] for an action. For instance, a smartphone or credit card approximating the payment terminal is naturally considered as an action going for a transaction. Therefore, NFC is a suitable technology for realizing embodied interaction with human bodies and physical objects.

The most profound HCI applications for NFC can be found in the works of Tangible User Interface (TUI) [1, 30, 42, 47]. Commercial products such as Nintendo Amiibo [1] and Lego Dimensions [2] used NFC as well in toys-to-life applications, allowing for the users to place NFC-tagged toy figures to unlock the associated digital content in games. In addition to detecting the presence of tagged objects, researchers also tried to track the states of tokens using NFC. One example is Project Zanzibar [53], which explored multi-object tracking, stacking, and translation using NFC. NFCSense [37] also leveraged the high data rate of NFC and physical constraints to further retrieve the transient states of NFC tokens such as speed and frequency to detect actions or measure an object's movement.

To support mobile and ubiquitous computing applications, NFC readers are increasingly equipped with smartphones and even smartwatches. However, the short sensing distances require the users to initiate the tasks by making extra efforts with their hands. To harness the benefits of different wearing locations, researchers have explored different wearable NFC devices, such as badges [12], pocket [56], gloves [17], bracelet [4, 17], wristband [15], ring [9] and finger-worn devices [37, 38]. Previous work also uses a wearable NFC reader for supplying power and retrieving data from battery-free sensors attached to the human body for vital signs and body motion monitoring [3, 8, 28, 45]. These systems either require clothing or additional wearable to incorporate an individually-powered readout circuit above each sensor or relied on large NFC readers integrated into the surrounding of the human subject. When there are multiple sensing locations apart from each other, the trade-off between wearing multiple NFC readers and the maintenance cost becomes significant. A user has to maintain and sustain additional batteries and hardware components for different body parts, aside from the existing personal NFC devices (e.g., a smartphone).

2.3 Near-Field Relays: Theoretical Background

Near-field relay [18, 39] is a passive circuitry that can extend the read range of an NFC reader. A near-field relay circuitry consists of two coils connected with transmission lines, which is a pair of parallel conducting wires. One antenna coil receives the NFC signal based on magnetic induction and then relays the signal through the transmission lines to the other antenna coil, acting as a duplicated NFC reader/writer that radiates the signal for an external device, as illustrated in Figure 2a.

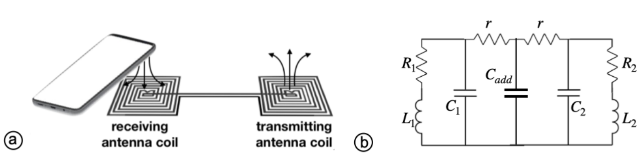

Figure 2: Two-coil Near-field relay: a) operation principle; b) equivalent circuit, where the addition capacitor C_{add} makes both coil size and transmission line's length adjustable.

Extending from Garnier et al. [18], the equivalent circuit of a 2-coil relay is shown in Figure 2b. The circuit consists of two identical parts connected with a small resistor r, which is the resistance of the transmission lines. The two parts represent the end of receiving and transmitting antenna coils separately. Each part contains an inductor L in series with a resistor R, which are the simplified components of a coil, and a capacitor C, which represents the capacitance of the transmission lines of half-length. When the relay is made of low-ohmic conductors, the ohmic loss is negligible and the power loss is minimized when $C \approx \frac{1}{(2\pi f)^2 L}$, where $f = 13.56 \times 10^6$Hz is the target frequency.

The inductance L of a single-layer relay coil can be calculated according to the formula described in the prior work [43]

$$L = K_1 \mu_0 \frac{n^2 \bar{d}}{1 + K_2 \rho} \tag{1}$$

where μ_0 is $4\pi \times 10^{-7}$, n is the numbers of turns, $\bar{d}$ is the mean of the outer and inner diameter ($\frac{d_{out}+d_{in}}{2}$), ρ is the filling ratio of the coil ($\frac{d_{out}-d_{in}}{d_{out}+d_{in}}$), K_1 and K_2 are variable dependent on the shape of coils (e.g., square, circle, or octagon coils). For instance, $K_1 = 2.34$ and $K_2 = 2.75$ are used for calculating the L of a square coil design.

The total capacitance C of the relay is mainly determined by the capacitance of half-length transmission lines C_{trans} (Figure 2b), which can be expressed as a linear function over the length l as described by Garnier et al. [18]

$$C_{trans} = k_1 \times l + k_2 \approx C \tag{2}$$

where k_1 and k_2 are unknown positive constants depending on different types of transmission lines. In general, the capacitance is directly proportional to the length of transmission lines.

Last, the effectiveness of an RLC circuit of antenna n is measured using a quality factor Q_n, which can be obtained by

$$Q_n = \frac{1}{R_n}\sqrt{\frac{L_n}{C_n}}. \tag{3}$$

In conventional full-speed near-field communication [16], a suitable combination of R, L, and C is chosen to make the NFC reader antenna's $1 \leq Q \leq 30$ to guarantee a sufficient bandwidth for a full-speed near-field communication [16]. Nonetheless, previous work also realized a high-Q NFC system with $Q = 125$ [48] that maximizes the power transfer efficiency in its applications.

2.4 Near-Field Enabled Clothing

Near-field enabled clothing is an emerging form that extends the read range of a single NFC reader to multiple locations on the wearer's body using a network of near-field relays on the cloth. In 2020, Lin et al. [39] developed a series of near-field enabled clothing as a wearable battery-free body sensor network to transfer data and power between a smartphone and sensors . Their prototype was composed of textile-based near-field relays, which are multiple conductor coils connected by transmission lines. The relays were made of conductive threads of electrical conductivity of 7.8×10^4 S/m (Shieldex 235/26 dtex 2-ply HC+B TPU) and embroidered on the clothing pieces. The technical capabilities demonstrated by Lin et al. are summarized as follows:

Read Range Extension. Lin et al.'s near-field relay implementation effectively extended the NFC reader's read range. By using an NFC reader (TI TRF7970A) providing constant output power of 200 mW with a smartphone-size ($3.7cm \times 5.2cm$) antenna, the relay of two

[1] https://www.nintendo.com/amiibo
[2] https://www.lego.com/en-us/dimensions/products

N = 10-turn (1mm-gap) D = 3.4cm coils and a l = 1m transmission lines reached a maximum power transfer efficiency of η = 10% (20mW) within 1.5cm lateral distance from the center of coil where NFC within the distance is possible. When l = 3m, a maximum of η = 6.3% can be maintained within the coil, which is still sufficient for sensing a reader physically *touched* a commercial NFC tag (TI TIDM-RF430-TEMPSENSE) that consumes $\sim$ 4mW.

Multiple Readouts. Multiple readouts were achieved by deploying a multi-terminal relay network where the coils were connected as a series and/or parallel networks. With an ISO/IEC 15693 NFC reader implemented a collision-avoidance mechanism, multiple NFC tags can be detected at $\sim$ 8 reads/s in Lin et al.'s implementation.

Multi-Hop Connection. A number N of near-field relays can also be wirelessly interconnected as an N-hop network by placing their coils in close proximity, which could be exploited to transmit energy and data between different articles of clothing. In Lin et al.'s textile-based implementation, the power efficiency was reduced to η < 2% after three hops, showing that the terminal could sense a physical touch after no more than two hops. Nonetheless, it was also mentioned that more hops can be realized by improving the overall power transfer efficiency using better types of conductors, such as copper (5.96×10^7 S/m).

Wetting, Deformation, and Stretchability. The textile near-field relays were also proven to be robust to deformation and wetting. The transmission lines can be stretched with a serpentine structure.

Applications. Lin et al. proposed applications for body motion monitoring using battery-less sensor modules, including spine posture monitoring and continuous exercise monitoring using a set of resistive strain sensors and temperature sensors.

2.5 Summary

The recent development of near-field enabled clothing [39] has demonstrated a set of promising technical capabilities enabled by this new form of passive, maintenance-free wearable NFC extenders. We recognized these emerging capabilities to be potentially useful for designing embodied and body-centric HCI. Meanwhile, we observed that the near-field enabled clothing pieces were mainly proposed for body-area networking rather than supporting embodied interactions between the users and other individuals, objects, and environments [7]. Also, it is unclear how to customize and fabricate the clothing to fit the dimensions of the bodies of different users to facilitate their individual needs in HCI. Therefore, in this paper, we aim to systematically explore the embodied, body-centric HCI aspects with the near-field enabled clothing technology.

3 DESIGN AND IMPLEMENTATION

The method we use to explore the design space of body-centric interaction with NFC devices can be broadly categorized as research through design [58], in which the design work in the applications domains will drive the exploration of both problems and solutions in the process. In this section, we first exemplify personal and interpersonal interaction with reflections on the technical requirements. Then, we revisit the technical background and available implementation methods, provide a pipeline for prototyping with technical validation, and then apply the obtained findings in a jacket implementation that realizes the proposed concept.

3.1 Body-Centric interaction with NFC Devices

According to the existing technical capability addressed in Section 2.4, textile-based near-field relay techniques support at most 3m of extension (for touch interaction) and two-hops of serial connection, and such results can be improved by using more efficient conductors which is more conductive. Therefore, we first exemplify a few plausible (inter)personal body-centric interaction with NFC devices using their body landmarks.

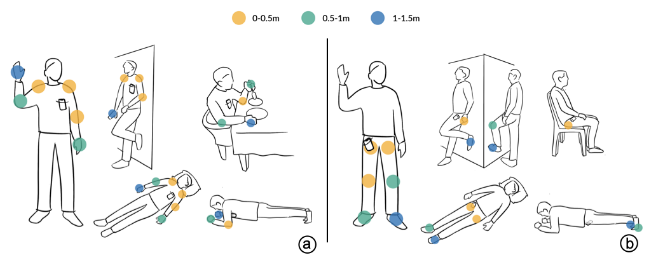

Figure 3: Examples of personal body-centric interaction: (a) with an upper-body garment; (b) with a lower-body garment.

Personal Body-Centric NFC Interaction. Figure 3 shows the plausible body-centric interaction that a user of NFC could perform when reading a tag on vertical or horizontal surfaces with an NFC-enabled phone placed in the pocket. For an upper garment (Figure 3a), we assumed that the personal device is placed in the front pocket on the left chest. For a lower-body garment (Figure 3b), we assumed that the phone is in the pocket on the left thigh for the lower-body garments. Various body-centric interaction could be realized by applying different lengths of NFC relays to extend the phone's reading distances from the pocket to the body landmarks. These cases can be generalized to different phone placement locations or different devices (e.g., a smartwatch). With a multi-hop connection, the relay terminal between the upper- and lower-body garments can also be connected in series to increase the access points and use cases.

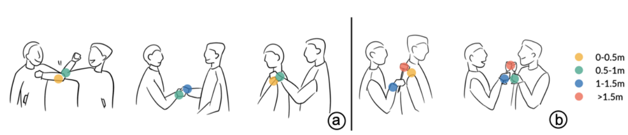

Figure 4: Examples of interpersonal body-centric interaction when two people are wearing the same upper-body garment: (a) using their bodies; (b) using relay-embedded props.

Interpersonal Body-Centric NFC Interaction. Figure 4 shows the plausible body-centric interaction when the two users are wearing the same type of upper-body garment (Figure 3a). Based on two hops of extensions, the users can use the body landmarks to perform various symmetric or asymmetric interpersonal interaction for exchanging information (Figure 4a). Moreover, with physical props installed with an NFC relays, it is even possible for the users to interact with each other through a physical prop (Figure 4b).

3.2 Design Guidelines

Based on the examples illustrated in Figures 3 and 4 and the theories explained in Section 2.3, we provide design guidelines for optimizing the design of NFC relays.

- *G1*: We suggest *using highly conductive materials for building the relays* to make wireless power transferring more efficient because the transmission lines might be long and multi-hop connections may be needed.
- *G2*: We suggest *making the transmission lines just long enough.* Depending on the location of the body landmark, the required transmission lines length may vary. Compared to relays of excessively lengthy or shorter transmission lines, a relay with proper length is easier to deploy on human bodies.
- *G3*: We suggest *making the dimensions of coils, including the relay coils or the tag coils, similar to each other* so the coils can achieve better coupling efficiency as well as read range for power and data transfer in NFC [16].
- *G4*: We suggest *making the coils larger when the body landmark is large enough* because they are easier for users to align with the target and make the detection range longer [16]. Otherwise, it is preferable to use as-large-as-possible coils to fit smaller body landmarks.

Based on these guidelines, we explore fabrication methods that are accessible and friendly for designers to realize these sketches to bring them to reality.

3.3 Prototyping Near-Field Relays

Figure 5 shows the four methods that we considered for realizing the near-field relays for Body-Centric NFC, including digital embroidery, heat transferring vinyl-cut copper sheets, and two industrial printed circuit fabrication methods.

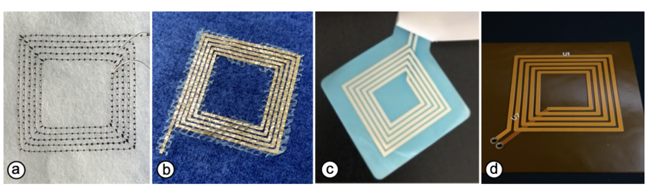

Figure 5: Exploration of fabrication techniques: a) embroidered conductive yarn on the fabrics; b) heat transferring a vinyl-cut copper sheet onto the fabrics; c) printed silver nanoparticle ink on a thermoplastic sheet, which can be affixed to the fabrics with heat; d) flexible printed circuit board.

3.3.1 *Digital Embroidery on Fabrics.*

Embroidering highly conductive yarn directly on the fabrics (Figure 5a) was first considered. Following the successful demonstration in previous work [21], we used a conventional digital embroidery machine (Brother M280) to fabricate a 40mm×40mm 5-turn ($d_{in} = 23.6mm$) $1.38\mu H$ square coil using Liberator40, a highly-conductive ($< 1\Omega/m$), flexible and solderable type of silver-plated conductive yarn that is more preferable than other types of conductive yarn of higher resistance and lower solderability. However, after a few successful rounds of implementation, we found this method limited our exploration for three main reasons: 1) the varying tensions between the upper and bobbin threads affected the reproducibility of the coils, 2) the efforts of machine preparation and extensive post-processing (e.g., wire cutting) slowed down the fabrication, and 3) the machine's small frame size ($10cm \times 10cm$) limited the fabrication of transmission lines. A more reproducible, low-effort, and scalable fabrication method is more desirable in the context of our work.

3.3.2 *Industrial Printed Circuit Fabrication.*

Regarding reproducibility and scalability, we also explored two advanced, industrial fabrication methods, but found them both less practical for our design exploration. One method is printing silver nanoparticle ink on a thermoplastic sheet (Figure 5c), which allows for making flexible circuitry that is reliable for frequent bending. The thermoplastic sheet allows the circuitry to be affixed by heat ($130°C$) that does not damage the fabrics. Although this method is very suitable for making daily wearable products, we did not use this method not only because the ink's high resistance ($\sim 390\Omega/m$) prevents us from making long transmission lines or multi-hop networks but also because it does not support post-processing (e.g., soldering). Another method that we considered is flexible printed circuits (Figure 5d), which achieve a conductivity comparable with the vinyl-cut copper sheet, provide higher durability for frequent bending operations, and support straightforward post-processing (e.g., cutting and soldering). However, fitting the circuit board to a piece of fabric is not easy due to the rigidity of the common Kapton substrate. In general, these industrial fabrication methods are also less flexible and affordable than personal fabrication methods.

3.3.3 *Our Method: Transferring Vinyl-Cut Copper Sheet to Fabrics.*

Figure 5b shows an example of a heat-transferred vinyl-cut copper sheet. Similar to the industrial printed circuit board method, this method supports personal fabrication of highly conductive circuitry, which satisfies the design guideline *G1*. This method also provides post-processing (e.g., soldering components) that is easier than inkjet printed circuit, higher replicability and fabrication hardware availability than digital embroidery, and more flexibility (less time and costs) than two industrial printed circuit fabrication methods.

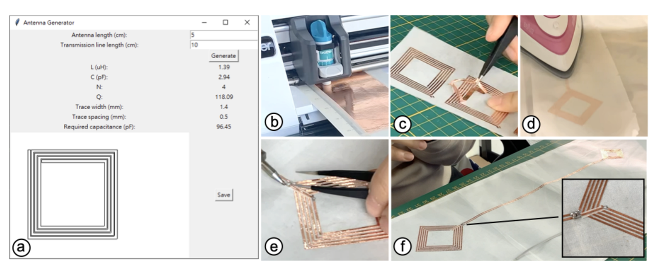

Figure 6: Process of heat transferring vinyl-cut copper sheet onto the fabrics: (a) generating an circuit design as an SVG file based on the high-level specifications; (b) cutting the copper foil with a vinyl cutter; (c) removing excessive materials; (d) transferring the vinyl-cut coil to the fabrics with heat; (e) adding an extra capacitor; (f) results.

Workflow. Figure 6 shows our workflow of fabricating near-field relays through heat transferring vinyl-cut copper sheets onto fabric pieces. We generate the coil design using a software tool (Figure 6a) that we implemented based on the theories mentioned in Section 2.3. First, the designer measures the desired coil size and transmission line length according to the design guidelines *G2*, *G3*, and *G4*, and enters these values with the target inductance (e.g., 1.4uH). The software generates an SVG file for vinyl cutting for making a $Q \sim 125$ relay. When the target inductance is impossible with the provided the coil size because of the limitation of vinyl cutting, the software suggests adding a parallel capacitor C_{add}, where

$$C_{add} \approx \frac{1}{(2\pi f)^2 L_1} + \frac{1}{(2\pi f)^2 L_2} - C_{trans} \tag{4}$$

and displays the required additional capacitance C_{add} can complement the insufficient capacitance of the transmission lines as shown in Figure 2b. The additional capacitor ensures that the relay function properly with the transmission lines' length (*G2*) and the coil size (*G3*, *G4*). Then, we attached copper tape to iron-on adhesive substrate [3] and used a vinyl cutter to cut out the coil (Figure 6b). The knife height of the cutter was carefully adjusted once to only cut the copper tape and avoid cutting the adhesive substrate, so the unwanted part of the copper tape can be easily removed with tweezers (Figure 6c). Then, we ironed the finished coil and transmission lines on a piece of fabric (e.g., cotton) (Figure 6d). Then, we soldered the transmission line between the coils. and add a small capacitor of C_{add} (Figure 6e). Notably, the capacitor added to the extender can be as small as a $1.5mm(W) \times 0.85mm(L) \times 0.45(H)mm$ 0603 surface-mount chip, which is even much smaller than a knot in textile, as shown in Figure 6f.

Reproducibility. We did two simple tests to understand the reproducibility with the vinyl-cutting copper foil method. In the first test, we fabricated twenty-five samples of 40mm×40mm five-turn ($d_{in} = 23.6mm$) $1.38\mu H$ square spiral coil antenna (Figure 5b) using copper foil and a Roland Stika SV-8 vinyl cutter and measured their inductance using DE-5000 LCR meter. The mean inductance error of the samples is low as $M = 2.6\%$ ($SD = 1.5\%$), which is about 0.036 μH. In the second test, we fabricated transmission lines with two lines of copper tape of 0.8mm-width trace and 0.5mm-spacing and measured the capacitance change over the lengths of the transmission line from 100 mm to 1000 mm on the cotton-fabric substrate, and then computed a linear regression. The shows results in a very strong linear correlation between the capacitance C (pF) and the lengths l (mm) of the transmission line ($C = 0.026l + 0.095, R^2 = 0.997$), which is congruent with Equation 2 and allows for the software to calculate the transmission lines capacitance and length based on this specification. Both results show a high reproducibility with our fabrication method.

Alternative Components. We also adopt widely-available flat cables and ceramic capacitors to ease the prototyping. Figure 7a shows examples of working NFC relays in three different transmission lines lengths (20cm, 15cm, 10cm) and two different coil sizes (25×25mm, 40×40mm). Each of the flat (1.27mm-thick × 2.54mm-wide) cables used in these examples consists of two 1.27mm-spacing insulated 14-strains of 28AWG copper multi-core wires, which can withstand frequent bending operations. Based on the same measurement method, we also obtained a very strong linear correlation between its transmission lines capacitance C (pF) and its lengths l (mm) ($C = 0.035l + 0.4, R^2 = 0.996$) that is congruent with Equation 2 and allows us to identify a proper C_{add} for compensation. The ceramic capacitors in a dual in-line package (DIP) in these examples are larger than the surface-mounted components, but they are widely available and generally easier to solder.

[3] https://www.vlieseline.com/

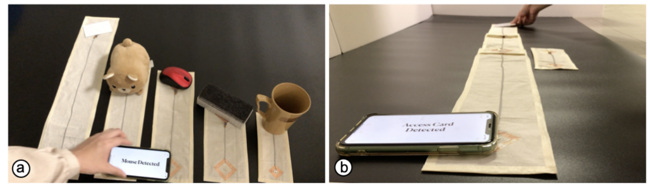

Figure 7: Near-field relays: (a) different transmission lines length and coil sizes; (b) multi-hop series connection.

Multi-Hop Relay Network. Figure 7b shows that a multi-hop connection of relays realized with magnetic connectors (Figure 8b). Every connection can read an NFC tag. Each connector consists of two 4mm (diameter) × 1mm (thick) N35 neodymium magnets, one north, and another one south. With 0.8mm-thick fabric insulation layers in between, the connector creates 0.88N force that holds two pieces of the coil antenna together from their opposite side. This connector keeps the physical location and orientation alignment between the two antennas without an electrical connection. These magnets are much smaller than the coils and distant from them, so the magnets do not introduce disruptive inductance to the coils.

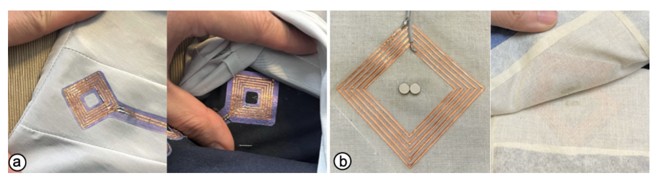

Figure 8: Coil alignment methods: (a) primitive alignment, which is done by sewing two pieces of fabrics together; (b) magnetic connectors that support snap-on alignment.

3.4 Technical Evaluation

With samples of relays implemented by using the aforementioned methods, we conducted two studies to understand the parameters for implementing the near-field clothing.

3.4.1 *Study 1: Length of Transmission Lines and Coil Sizes.*

The first study examined the tag reading distance of our relay implementations of different coil sizes and the transmission lines length.

Apparatus. Eight relays of two square coil sizes (w_c=[25,40]mm) and four transmission lines lengths (l_t=[100, 200, 400, 800]mm) of our implementation were used in the study. We evaluated the performance of the relays by measuring the reading distance between a 30mm-diameter NTAG213 NFC tag and a relay's transmitter coil, which is connected to the back of an iPhone 11 at the location of its NFC reader antenna. To stably measure the reading distance, we placed the relays on a table and kept the top side of the smartphone (i.e., the position of the NFC reader) aligned and in contact with the receiver coils. Then, we put the NFC tag on a height-adjustable holder made of acrylic, which stands right on the relay's transmitter coil to allow us to tune the distance between the coil and the tag, as shown in Figure 9a.

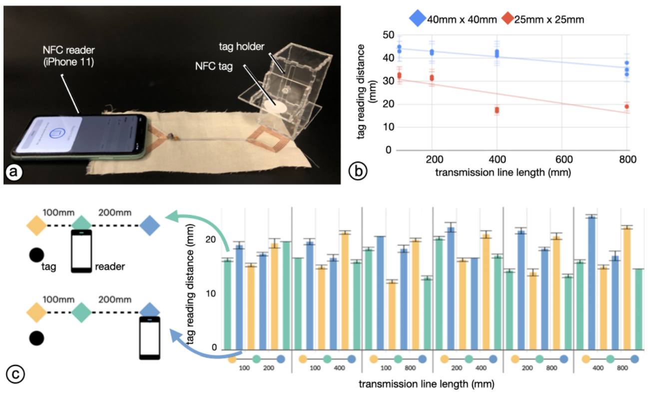

Figure 9: Evaluation: (a) experimental apparatus for study 1; (b) results for study 1; (c) results for study 2.

Procedure. The measurement of reading distance started by setting the height of the tag holder as 80mm. Then, we manually lowered the height until the phone can stably read the tag. The final height of the holder is recorded as the reading distance. We repeated the measurement three times for each relay. In total, 8 (relays) × 3 = 24 samples were collected.

Results. Figure 9b shows the results of measurements, where each point represents one measurement sample. The original reading distance of iPhone 11 ($M = 32mm, SD = 1.4mm$) is shorter than the relay with the 40mm-wide coil ($M = 41mm, SD = 3.6mm$). All relays were functional and maintained a reasonable tag reading distance ($M = 33mm, SD = 9.8mm$) for near-field communication. This finding supports the design guideline *G2* as it shows the users can freely adjust the transmission lines' length for their purposes. In general, the longer relays have a shorter reading distance, because the resistance is proportional to the length of the transmission lines. This finding supports the design guideline *G1* as it indicates the important of using highly-conductive materials for relay fabrication. The users can freely adjust the transmission lines length for their purposes. When the coil size is smaller, the reading distance is also shorter because the magnetic field induced by the smaller coil is weaker at a longer distance [16]. This finding supports the design guideline *G4* as it shows larger coils provide longer reading distances. It is also the reason why the relay with the $w_c = 40mm$ coil ($M = 41mm, SD = 3.6mm$) has a longer tag reading distance than the original iPhone 11. Nonetheless, the longest ($l_t = 800mm$) relays with the smallest ($w_c = 25mm$) coil still have an average tag reading of 19mm ($SD = 0mm$).

3.4.2 *Study 2: Series Connection.*

This study investigates if the implemented relays can support at least two hops of extension without a significant impact on the tag reading distance.

Apparatus. Four relays of four transmission lines lengths ($l_t = [100, 200, 400, 800]mm$) with $w_c = 40mm$ square coils were used in the study. Other apparatus are the same as in Study 1.

Procedure. We traversed the possible NFC reader and tag positions by putting the smartphone NFC reader on one of the three coils and measured the tag reading distances on the remaining two coils. For each location, measurement procedures are the same as in Study 1. In total, C_2^4 (2-combination of 4 extenders) × 3 (NFC reader positions) × 2 (tag position) × 3 = 108 samples were collected.

Results. Figure 9c shows the measurement results, where the X-axis is the measurement condition and Y-axis is the average tag reading distance of three samples. Among all the possible combinations of a two-hop relay network, the overall mean tag reading distance is 18.1mm ($SD = 3.01mm$) at every point of measurement. This finding supports the design guideline *G3* as it shows a reliable multi-hop series connection can be achieved by using coils of similar dimensions. When the NFC reader is placed at the end coil, the tag reading distance of the coils in the middle coil ($M = 16.4mm, SD = 1.9mm$) is worse than at the other end coil ($M = 21.4mm, SD = 1.7mm$). When the NFC reader is placed at the middle coil, the tag reading distance ($M = 16.6mm, SD = 2.3mm$) is slightly lower than the NFC reader placed at the end coils ($M = 18.6mm, SD = 3.0mm$). Overall, the results show our relay implementation supports building a simple two-hop network for extending the NFC reader to at least 120cm with sufficient usability for reading the NFC tag.

3.5 Making a Proof-of-Concept Jacket

Based on the findings, we designed and fabricated a proof-of-concept jacket, namely NFCe, with the relays, as shown in Figure 10. A jacket that embeds a two-hop relay network built with two series-connected $w_c = 25mm$ square-coils relays, one of $l_t = 100cm$ transmission lines and another one of $l_t = 60cm$ transmission lines. We first briefly tested this two-hop relay network with the same apparatus of studies 1 and 2 and reassured that the tag reading distance is more than 15mm when the NFC reader is placed at the middle coil and the tag is read at both ends. Then, we made a pocket that is slightly larger than the smartphone (i.e., iPhone 11) near the waist on the left side, a common position for pocket design, allowing the users to slide the phone in smoothly.

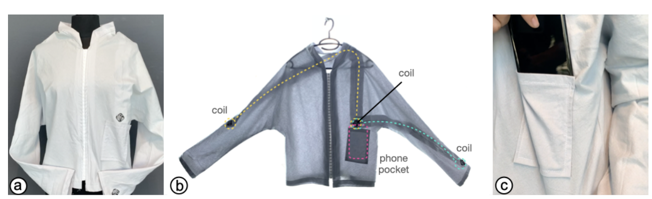

Figure 10: Proof-of-concept NFCe jacket: (a) results; (b) locations of the relays; (c) phone pocket.

We affixed the relay network from the inside of the jacket, so it is not visible from others' perspectives. We fixed the middle coil at the location of the NFC antenna location of the smartphone in the pocket, one end coil to the right elbow's location, and another end coil to the left wrist location. To avoid the transmission lines from crossing and wrinkling, we reinforced the structure of the relay using inelastic cotton fabric, which can withstand high temperatures during soldering. Last but not least, we put logos at the three coils' location on the outside of the clothing as a visual cue for the users.

With a smartphone in the pocket, the user can read an NFC device with their right elbow or left wrist. The user can also extend their NFC-enabled smartwatch worn on the left wrist to their right elbow if there is no smartphone in the pocket.

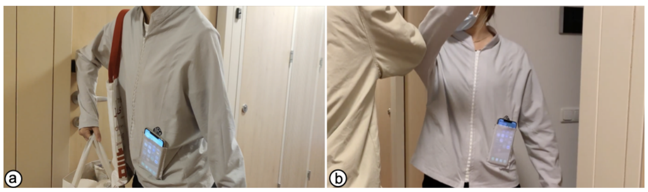

Figure 11: Example applications: (a) access control; (b) contact exchange through an elbow-bump.

Example Applications. With the garment design, we realized the two applications illustrated in Figure 1. Figure 11a shows an access control application. The user says *"hi phone, use my access card"*, and taps the NFC-enabled lock with the elbow to open the door. Figure 11b shows two users wearing the same type of garments bumped their elbows to exchange contact information. Both applications were implemented with the shortcut app in an iPhone 11, which provided audio feedback that informs the users when the operation is detected.

4 CO-CREATION WORKSHOP

To gather new application ideas in the design space and qualitative feedback about the technique from practitioners, we conducted a co-creation workshop with interaction designers and general users.

4.1 Method

Participants. Six participants (3 males, 3 females) were recruited. Three of them had at least three years of interaction and/or industrial design experience. Participants were evenly divided into three groups of two, one designer and one general user. General users and designers were informed to be co-designers during the workshop. All participants provided consent before the workshop.

Apparatus. Figure 12a shows a the toolkit for brainstorming and rapid prototyping. Since the focus of this study is on the application rather than fabrication, We used a prefabricated toolkit that includes six relays of a coil size of $w_c = 25mm$ and different transmission lines lengths l (100mm×1, 200mm×2, 400mm×1, 600mm×1, and 800mm×1) Each relay has built-in magnetic connectors (Figure 8b) so the participants can make an arbitrary length of relays by snapping them together to fulfill their needs. Additionally, we provide several NTAG215 NFC tags, paper tapes, scissors, and brainstorming materials. An NFC-enabled phone that provides audio feedback once a tag is read is also used during the workshop.

Figure 12: Apparatus for co-creation workshops: (a) prefabricated toolkit and brainstorming materials; (b) ideation phase; (c) prototyping phase.

Procedure. Participants were first interviewed about the experience of using NFC technology in their daily life. For those who did not know the NFC technology, a quick introduction was given. Then, our system was introduced to the users with a video explaining the proposed Body-Centric NFC interaction concepts with example applications. Then they tried on the proof-of-concept jacket to experience the ways to use it. Then, the participants spent about 20 minutes brainstorming, discussing, writing down or sketching out ideas (Figure 12b). They were asked to start by considering the existing NFC applications and then focus on how they wanted to use their body landmarks instead of their phone. The researcher informed the participants of the feasibility of the ideas if necessary. After the ideation, the co-designers were asked to perform an embodied sketching [41] session where each group picks one or two of their favorite ideas and uses the toolkit to prototype the wearable system and act the scenario out (Figure 12c). Finally, participants were interviewed to provide feedback and share their experiences.

4.2 Results

4.2.1 Phase 1: Ideation. In total 19 ideas were generated in the three workshops. They were recorded and categorized into 6 classes, including convenience (6), such as personal shortcuts; entertainment (5), such as games; IoT smart home (3), such as automation triggers; health (2), such as posture sensors; inventory management (2), such as item counters; and safety (1), such as hands-free operations through the cloth. 17 (out of 19) are personal body-centric interaction between the users and their surroundings, whereas 2 of them are interpersonal interaction between two persons. 15 (out of 19) ideas involved upper body landmarks (e.g., shoulders and elbow), and 4 (out of 19) ideas involved the lower body landmarks (e.g., knee and foot), such as detecting what tag the user stepped on. 10 (out of 19) ideas involved the body landmarks on their hands (e.g., wrist and backhand) when the users are in hands-busy scenarios or need to touch something without looking (e.g., when one is driving). Notably, 2 (out of 19) ideas involved specific scenarios, such as driving at the entrance of a parking lot, where the users may prefer not to use their phone for NFC because they may drop it. Last but not least, although the back was not counted as a body landmark in the first place, 2 groups of participants proposed to use their back to interact with their seatback.

4.2.2 Phase 2: Prototyping the Applications. Three ideas were prototyped and acted out by the groups. Figure 13a shows an interactive climbing wall with NFC tags on multiple climbing rocks. The user deployed the relays from the phone pocket to his hands and feet (climbing gloves and shoes). During rock climbing, the phone makes

Figure 13: Results of application prototypes: (a) interactive climbing wall; (b) inventory management; (c) sitting posture detection and relaxation reminder.

a sound when the user’s hand or foot touches a tagged rock to keep the climber motivated. Tapping the rock at the top, the wall takes a photo and sends it to the user, probably also via NFC. Figure 13b shows an inventory management scenario, where the user taps the bag with the cuff to record it when an item is consumed. Figure 13c shows a sitting posture detection and relaxation reminder. The participant put an extended coil on his back and a matrix of 3×3 NFC tags on the seatback of an office chair. When the phone reads the same tag for a long time, it prompts the user to stretch their body by moving their back to a different tag or inviting the user to stand up and take a break.

4.2.3 Phase 3: Interview. Overall the participants expressed a positive attitude toward the on-body NFC extenders as the implementation in the garments, such as *“I think it is very good and can solve the pain points in the (NFC) interaction process.”* Regarding the practicalities, participants generally raised their concerns about the comfort of wearing, washability, and adaptability. They look forward to waterproof near-field enabled clothing for daily use and hope that this will not significantly reduce their choice of clothing materials. Participants also pointed out that different smartphone brands and models have different locations of the NFC antenna, so it is difficult to design a universal pocket. One participant recognized that *“a pocket dedicated to putting a mobile phone may become a trend in the future,”* but more participants seem to be more willing to put the phone where they are accustomed to, such as in their thigh pocket.

Regarding the applications and scenarios, three (out of six) participants discussed wireless payment but felt insecure about placing a large number of coils on their bodies. An extra step of authentication (e.g., performing a specific gesture) might be needed. A participant mentioned that clothing can be useful in a sterile ward and biological laboratory, where users need to wear special clothing to prevent the invasion of germs and do not want personal devices (smartphones) to be contaminated.

4.3 Summary

With an accessible and easy-to-use toolkit, the co-designers were free to design the bodily performance and the expressions of physical objects during the ideation and prototyping sessions in a real-world setting. These participants also made clear sense of the coupling [14] between their performance on the tagged physical artifacts and the audio feedback they received from the NFC-enabled phone. From the results, we found that body landmarks on hands are still useful in many cases, so extending the relay from the cloth to the landmarks on their hands is desirable. It is also vital that such an extension should not compromise the comfort of wearing. Last, since audio feedback may not be acceptable for social situations [35], a more private and subtle feedback modality needs to be further explored.

5 EXPLORATORY MAKING

Based on the findings summarized in Section 4.3, we further investigate the design opportunities and hidden technical issues through a series of exploratory making [58].

5.1 Extensions and Improvements

On-Body Extension. Near-field clothing can be extended by on-body relay stickers. Figure 14 shows a piece of on-body sticker that further extends a right elbow coil to the right hand’s wrist, so the user can also use the right hand’s wrist to read a tag associated with a personal shortcut.

Figure 14: The elbow coil on the jacket is extended by an on-body relay sticker so the user can use her wrist to access a personal shortcut.

Wearable NFC devices can also be extended by on-body relay stickers. Figure 15b shows a relay sticker with a nail-mounted coil that extends the read range from an NFC smartwatch mounted on the wrist. With the nail-mounted coil, the system detects what mug is used by reading the NFC tag, which is embedded in the mug handle under the thumb. The smartwatch was implemented using an M5 Stack [4] platform with an NFC reader module. The thumbnail coil relay was implemented using a flexible printed circuit (FPC)

[4]https://m5stack.com

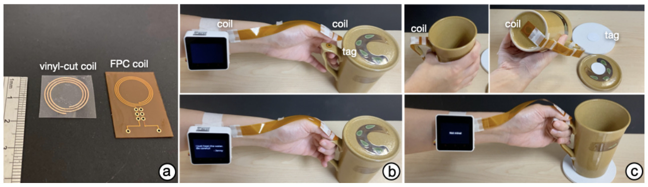

Figure 15: Near-field relays for fingertip: (a) thumbnail-size coils; (b) reading a tagged mug; (c) reading a tagged coaster through a relay-embedded mug.

board (Figure 15a). A future version can consider incorporating with woven antenna [28] to improve the comfort of wearing.

On-Object Extension. Figure 15c shows a relay-embedded mug that further extends the read range of the nail-mounted coil. Through the relay mounted on the mug handle, the system detects the tag on the coaster. The coil size at the bottom of the mug can be further enlarged to make the alignment easier. Different adaptations can be applied to everyday objects for realizing the examples in Figure 4b.

Stretchability. Making the on-garment electronics stretchable is key to the comfort of wearing. A stretchable garment can fix the location of the antenna coil as well. Figures 16a-d show sine-wave shaped transmission lines and antenna design that increases the stretchability of the relay. Flat cables are more reliable yet more difficult to be fixed on the fabrics (Figure 16a). Copper tape is easy to fabricate and fixed on the fabrics and can be stretched at 10% as shown in Figure 16b, while it's fragile as it breaks when being stretched further. Figure 16c shows a better solution which adds a layer of a flexible thermoplastic (TPU) sheet, which is not stretchable, between the fabric and copper tape and cut the TPU sheet into sine-wave to allow the rest of the fabrics to be stretchable. Figure 16d shows a coil fabricated using the same technique.

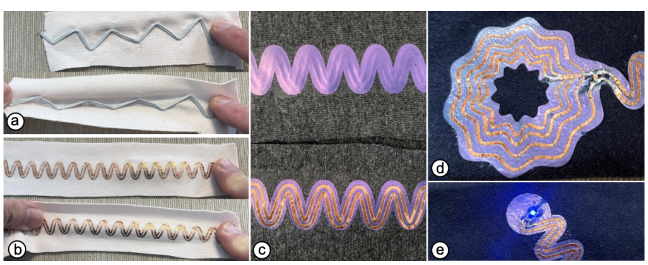

Figure 16: Improved forms of relays: (a) stretchable transmission lines made of flat cables; (b) stretchable transmission lines made of copper foil; (c) thermoplastic reinforced copper-foil transmission lines; (d) thermoplastic reinforced copper-foil coils; (e) transmission lines with an LED.

Haptic and Visual Feedback. Haptic feedback can be easily added by vibrating the phone in the pocket, but it's challenging to deliver haptic feedback at the location of coils. Delivering visual feedback through the phone in the pockets might be ineffective for the wearer due to poor visibility, but might be useful for others [29]. Additionally, visual feedback can be delivered at the location of coils using a tiny LED connected to the transmission lines, as shown in Figure 16e. Figure 17 shows an example of an LED in a series connection to the relay, the LED flashes when an NFC reader is operating. This is possible because the LED harvested energy from the act of an NFC reader. The visual feedback can be expressive because the LED flashes at a different frequency when there is an NFC tag being read. With advanced control of the NFC reader, an expressive set of visual feedback [24] can be further realized.

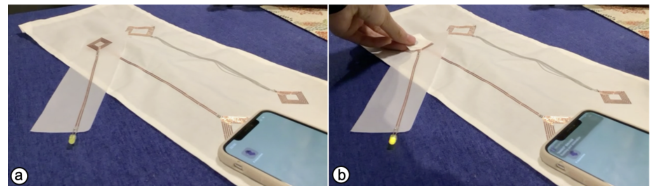

Figure 17: Visual feedback. The LED in a series connection to the relay flashes when an NFC tag is read by the reader.

5.2 Plausible Design: Long-Sleeve Shirt

Combining the results of exploration, a long-sleeve shirt (Figure 18) is skillfully crafted to show an advanced integration of a relay network with the LED nodes. The shirt has two layers: 1) non-stretchable outer layer, which has a phone pocket; 2) inner layer, which is a stretchable long-sleeve shirt that is comfortable to wear. The two layers are sewn together so the relays between both layers are primitively aligned (Figure 8a). On both sleeves, sine-wave TPU-reinforced transmission lines (Figure 16c) and the coils (Figure 16d) were implemented on the sleeves to make the sleeve stretchable. A tiny surface-mounted LED (Figure 16e) is added to each arm so visual feedback can be perceived when the reader is reading an NFC tag. The end of each sleeve is fixed between the thumb and index so the locations of the coil are fixed even when the user's arm is bent. Unlike the jacket (Figure 10) that hides the transmission lines inside, this shirt intentionally leaves the relays exposed as part of the aesthetics that are potentially fashionable [19, 52].

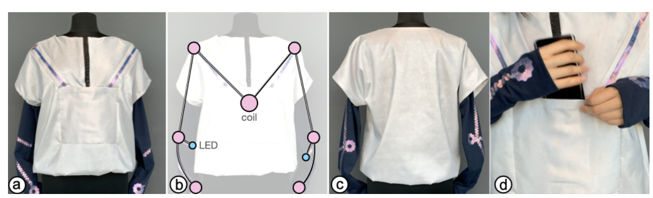

Figure 18: Long-sleeve shirt: (a) front view; (b) relay network with the LED nodes; (c) rear view; (d) pocket.

Applications. Figure 19a-d shows an interactive fitness training with this shirt. With passive tags attached to the dumbbell, yoga mat, and knee, a range of activities can be counted and logged by a mobile app that tracks the tag presence with the ID. Visual feedback can be observed through the user's peripheral vision. Figure 19e also show an inventory management app that allows users to log their activity with the finger knuckles on their backhand.

Figure 19: Applications of long-sleeve shirt: (a-d) interactive fitness training; (e) inventory management.

Limitations. The tag reading distance of this shirt was noticeably shorter and unstable because the near-field relay network has more hops, the inductance and capacitance of the relay slightly vary when stretching, and the fractures and breaks of traces after intensive operations. Although we did not attempt to further optimize the stretchable antenna using the methods proposed by Xu et al. [57] or moving to a more reliable fabrication method such as digital embroidery, this clothing piece still demonstrates a good practice of designing stretchable near-field enable clothing.

6 DISCUSSION

In this section, we reflect on our design objectives and limitations to inform future research directions.

Embodied Interaction Design Toolkit Based on NFC. This paper presents an accessible method and easy-to-use toolkit that lower the threshold of fabricating flexible, extensible, and scalable NFC extenders on clothing. We expect this toolkit useful for enabling non-technical designers to prototype embodied HCI with their existing mobile NFC devices (e.g., NFC tags, smartphones, and smartwatches) even when they are not familiar with electronics and programming. Such a prototyping tool is desired for body-centric computing in the application fields of health, well-being, sport, and entertainment [44]. Furthermore, we see this toolkit as useful for engaging users of non-formative bodies [51], as the simple technique of adjusting the length of transmission lines with an additional capacitor C_{add} (Equation 4; Figure 2b) welcomes designers to customize the relays to provide tailored bodily experiences for them. The toolkit also has the potential to contribute to the realization of somaesthetic appreciation designs [27] because the lightweight, passive, maintenance-free near-field enabled clothing technology is unobtrusive for people's somatic practices.

Antenna Optimization. The near-field relay design used in this work was tested using a similar antenna testing apparatus as Lin et al. [39], as shown in Figure 20. With a NanoVNA V2 vector network analyzer (VNA), standard 50Ω SMA connectors, and commodity NTAG215 NFC tags, we verified the power transferring efficiency of the relay samples at the 13.56MHz. Nonetheless, we found it difficult to translate the signal strength measurement (i.e., *dB*) to the actual user experience because the NFC reader antenna configuration of an off-the-shelf NFC phone is often unknown. Therefore, referring to Lin et al. [39], we report the tag reading distance in our study to reflect on the sensing distance using our NFC reader (i.e., iPhone 11). We also informally tested the performance of near-field relays with Android phones and got similar results. Although the generality of this way of reporting is limited as it does not generalize to other types of NFC readers, such as other smartphone models, it informs our design decisions in the process and makes the results replicable. We invite future work to further examine the performance of different types of NFC readers with our technique.

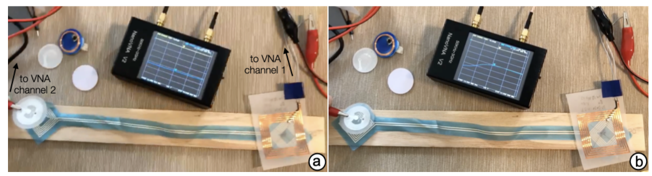

Figure 20: Antenna testing: (a) apparatus; (b) example results of S11 (yellow) and S21 (blue) measurements.

NFC Capabilities and Devices. This work focus on the body-centric interaction enabled by the near-field relays and the extension technique. Therefore, we simply demonstrate the rudimentary tag reading capability. Nonetheless, a successful tag reading can represent a valid data communication that has been established because the identification passed the error correction code examination. More sophisticated NFC operations such as writing a tag or access control can happen in a valid communication channel. Another limitation is that the rigid NFC phone in the cloth pocket is still a bit bulky and may affect the comfort of wearing. Future work may consider ways to loosely couple the phone and the cloth (e.g., an external pocket connected to the cloth with wire) to make the cloth more comfortable for an extended period of use, or further exploiting the relay technique with an NFC-enabled wearable device, such as a smartwatch.

Body-Centric Interaction with Surroundings. Beyond the body, near-field relays could also be used in the periphery of the body, such as the tool a user grasps, the sofa a user sits on, and the floor a user stands on, which can augment the user input and the system's contextual awareness. For example, hand tools could be an extension of human hands, so a graspable tool applied to a relay can extend the on-body NFC reader's reach. Figures 15b and 15c show that the object's visual or physical affordance can support its users to align the relay coil on their hand to the object's coil with a grasp. With those objects as a physical extender in hand, the users can use the tool to read other tagged tokens beyond their original hand reach. Once the user released the object, it stays passive and maintenance-free and still serves its original physical purpose for others who do not wear a reader.

Fabrication for Long-Term Wearability. Although the copper-foil relays survived the exploration sessions and workshops, they tend to fracture and break after frequent bending operations, especially at the location where soldering was applied. Also, in high-humidity environmental conditions, such as raining or sweating, or after it is washed, the surface oxide problem may also deteriorate its performance over time. Therefore, we still recommend future researchers apply digital embroidery (Figure 5a) as the fabrication method for non-exploratory activities, such as making a more reliable product for a longitudinal study. The designers need to be mindful that the total resistance introduced by the chosen conductor material and the dimension of relay circuitry should be low enough to keep the chosen $Q \geq 1$, depending on the chosen L and C. For rapid prototyping, emerging materials and techniques such as highly-conductive and stretchable inkjet circuit printing [32] and iron-on PCB circuits [5, 33] are also promising if their fabrication hardware and materials are more available for designers and practitioners.

Fitting the Body Landmarks. Deploying near-field relays on body landmarks that are smaller or larger or require flexion is challenging. Regarding smaller body landmarks such as fingertips and knuckles on one's hands, smaller single-layer coils made of other fabrication methods such as flexible printed circuits (Figure 15) can better fit in these smaller regions like a fingernail, but the Kapton substrate of FPC makes it uncomfortable for the body landmarks that requires flexion. Future work can consider combining the embroidery with very-thin enameled wire (e.g., Textile Wire [5]) to make flexible and stretchable coils [46], because conventional vinyl cutter that cannot reliably cut thin (e.g., $< 0.5mm$-width) traces with copper foil limit the minimal size and density of coil winding. Regarding larger body landmarks such as back or hip, increasing a single relay coil's size may not be efficient because it may create blind spots in its middle. Instead, it is more efficient to use an array of coils to cover a larger area. Leveraging the rigid components such as a clothing button [11] to achieve clothing integration is also possible for some positions, such as a sleeve close to the wrist.

7 CONCLUSION

Through the lens of embodied and body-centric interaction, we explored the HCI opportunities enabled by near-field enabled clothing [39], an emerging technology that can passively extend the read range of an NFC reader (e.g., smartphone) to multiple body landmarks of the wearer. The research-through-design exploration aimed to transform such an emerging technology into an approachable material for product and service design and empower designers to embody the interaction experiences with their design skills. We have exemplified plausible body-centric interaction designs within the boundaries of technological capabilities and provided design guidelines that are examined in the technical evaluation. We have explored suitable prototyping techniques and developed tools for the designers to embody the interaction experiences as body-scale wearables. We have elicited insights from the co-design workshops and exploratory making activities and generated knowledge for future near-field enabled clothing or on-body UI designs for enabling embodied and body-centric interaction between the users and their surroundings. We sincerely hope this work will provoke more designer-centric exploration of emerging technologies.

[5]https://www.textile-wire.ch/

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