Hapt-Aids: Self-Powered, On-Body Haptics for Activity Monitoring

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Wearables are becoming increasingly useful, primarily due to their activity-monitoring features that enable various healthcare applications. Everyday devices like smartwatches, however, often have complex ecosystems and convoluted interfaces. These devices need constant charging and can be difficult to use, cumbersome for users interested in only simple applications. As an alternative, simpler everyday wearable, we present Hapt-Aids, self-powered on-body tags that passively monitor user activities and deliver haptic notifications. Our small-footprint devices 1) harvest energy from activity-specific sources, 2) use this energy as sensor information, and 3) convert this energy into haptic actuation using only analog hardware, without digital components or firmware. This structurally simple, triple-purpose design makes our system extremely low maintenance while being cost- and energy-efficient, leading to a friendly user experience. We present our proof-of-concept system design: a custom, unique architecture formed through theoretical modeling and evaluation studies, and we build four demo applications. Through in-lab benchmark testing and user studies, we demonstrate the potential of Hapt-Aids as alternative low-cost, easy-to-use wearables.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile devices**; Haptic devices.

Additional Key Words and Phrases: Energy Harvesting; Self-Powered; Haptics; Activity Sensing; Wearable Health

ACM Reference Format:
Vivian Shen, Xiaoying Yang, Chris Harrison, and Yang Zhang. 2025. Hapt-Aids: Self-Powered, On-Body Haptics for Activity Monitoring. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 9, 3, Article 129 (September 2025), 26 pages. https://doi.org/10.1145/3749468

1 Introduction

Monitoring user activities is critical in many health applications and is a unique strength of wearable devices. Commodity wearable devices have enabled us to track activities and exercises, providing notifications to users once a preset activity threshold is surpassed. For instance, a Fitbit wristband can be configured to vibrate at every 10,000-step milestone. Similarly, an Apple Watch alerts its user once their activity rings are closed, indicating their target activity amounts have been reached. These notifications can guide wearable device users toward healthier lifestyles by facilitating decision-making to improve their physical health.

However, today's wearables often function as generic computing devices, heavily fitted with complex ecosystems consisting of varying functionalities. This overhead requires additional components and thus power, increasing the cost of the system and also requiring frequent removal and recharging. Smartwatches are a representative example of these powerful yet complicated devices, and we position these at one end of the spectrum of

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ACM 2474-9567/2025/9-ART129
https://doi.org/10.1145/3749468

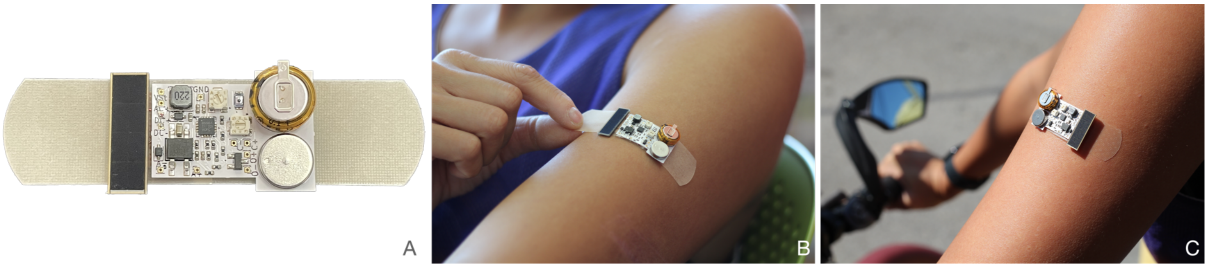

Fig. 1. Close up of an example functional Hapt-Aid (A). The user applies our small, wear-and-forget device to their arm (B) to monitor their sun exposure (C). This Hapt-Aid provides a haptic notification when the user has reached the recommended daily sun exposure; in this example, the vibration is triggered after an average duration of 43.9 minutes in an average sunlight illuminance of approximately 30 kLux across five repeated trials.

wearables (Figure 2). At the other end of the spectrum are passive stickers (such as band-aids and UV patches), which typically lack sensing, actuation, or computational capabilities and are limited to a single use case (i.e., covering a wound). However, they are passive, durable, and ultra-low-cost — key properties that contribute to their widespread applications. With our system, we envision a new type of device positioned towards this end of the spectrum. These devices are inexpensive, single-purpose but effective, support activity tracking, and provide user notifications, allowing users to wear and forget about them. Once our devices are worn, users can generally ignore them, making this technology "disappear into the background" of people's lives [69]. Accordingly, we ensure our wearable device maintains a minimal footprint while also eliminating the need for complex hardware, complicated instrumentation, and cumbersome wireless connections to external devices, such as pairing via Wi-Fi or Bluetooth. Additionally, to be "forgotten" during use, a system must be self-sufficient, capable of powering itself and delivering notifications without frequently demanding a user's attention, minimizing cognitive load.

To explore these design goals, we present Hapt-Aids: a variety of on-body tags that convert user activity energy into haptic actuation, notifying users when preset activity level amounts have been reached. To realize this vision, Hapt-Aids follow several design principles. (1) No batteries: instead, Hapt-Aids capture ambient and user-generated energy from target activities as power sources for the entire device, eliminating the need for user maintenance. (2) No visual attention: haptic output modalities provide non-intrusive notifications, ensuring compatibility with daily activities without requiring a user's visual attention. (3) No sensors: the energy gathered is coupled directly with the activity through the choice of energy harvester, so the amount of energy harvested can be interpreted as sensor data that quantifies the activity amount. (4) No digital components: the system is fully analog without digital components like microcontrollers, significantly reducing material cost and complexity. As an example, consider a Hapt-Aid that tracks a user's sun exposure, as seen in Figure 1. Using a solar cell as an energy harvester, the Hapt-Aid harvests solar energy over time and stores it in a capacitor, serving indirectly as an indicator of the user's cumulative sun exposure. Once the stored energy reaches a preset level, the Hapt-Aid will dump all its stored energy into a haptic actuator, notifying the user that their sun exposure has reached their recommended limit.

Prior work RF Bandaid presented a similar design vision, utilizing fully analog components to harvest RF energy and power wearable sensors for physiological monitoring [42]. We present Hapt-Aids as an alternative approach with an entirely new system architecture and a unique combination of features. This includes both the ability to power haptic actuators and the ability to directly use the stored energy amount as sensing information, since it is coupled directly to the activity, eliminating the need for external sensors. We emphasize that our work is less focused on achieving high-fidelity sensing and haptics, or comprehensive wearable functionalities enabled

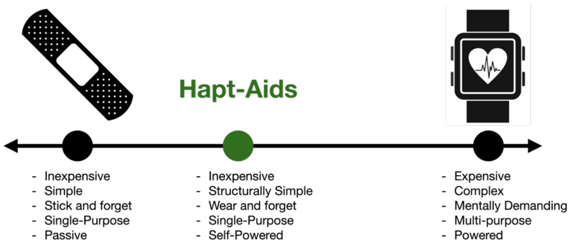

Fig. 2. On the spectrum of passive to active wearables, we envision Hapt-Aids to be somewhere between Band-Aids and smartwatches, borrowing ideas from each to create a device with a useful and unique mix of properties.

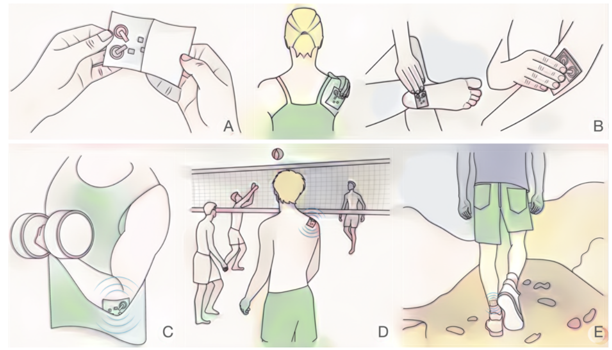

Fig. 3. Envisioned use scenarios of Hapt-Aids. Users can easily peel (A) and wear (B) the devices on multiple locations on the body, monitoring activities such as arm flex (C), sun exposure (D), and step counting (E).

by energy harvesting, but more on presenting a novel design scheme for standalone wearables where the resulting cost, power, and ease of use makes it a compelling alternative for activity monitoring despite some advanced functionality trade-off. In this research, we identify a set of wearable harvesters for harnessing energy coupled with user activities, and designed a custom circuit to leverage this energy for sensing and haptic actuation. To ensure the compatibility and practicality of Hapt-Aids, our circuit design includes essential user customization features (e.g., allowing a user to tune the threshold of target activity amounts for triggering notifications) and the ability to adapt to multiple energy sources (e.g., AC and DC power). We document our design process and rationale for the system design, which we evaluated with a series of in-lab benchmark tests. We built four proof-of-concept Hapt-Aid devices, and validated their efficacy with user studies. Our results show that end-to-end Hapt-Aids are compatible with multiple energy sources and able to create perceivable and understandable haptic feedback for our example activities.

We believe the new form factor proposed by Hapt-Aids could lower the barrier for activity monitoring in health applications across a broader range of use scenarios and to larger user communities. We summarize our contributions in the scope of this work as follows:

- A new analog system architecture to convert activity energy into self-powered haptics.
- Development and validation of four user activity tracking applications with our system featuring activity harvesters of different power profiles.
- Insights from user studies with four end-to-end activity applications that provide a solid footstep for future self-powered wearable haptic technologies.

2 Related Work

2.1 Energy as Sensor Data

In the literature, self-powered sensors can refer to (1) sensors with novel material characteristics that can generate differentiable power signals (e.g., triboelectric nanogenerators (TENGs)), which can be sampled and processed by an external computing unit [51, 75], or (2) specialized sensors featuring self-sustainable energy harvesters to provide power, replacing conventional batteries [34, 42, 66, 77]. For lightweight and compact wearables, sensor reduction and adaptive sampling have been explored to minimize power consumption [27, 40]. To further reduce power consumption, recent work has leveraged the contextual harvested energy as both a power source and

	Example System	Size	Cost	Reusable	Self-Powered / Battery-Free	Functionality	Notification
Smartwatches	Apple Watch	Medium	High	Yes	No	Varied	Haptic & Visual
Fitness Trackers	FitBit	Medium	High	Yes	No	Varied	Haptic & Visual
Pedometers	3DFitBud Clip-on	Medium	Low	Yes	No	Singular	None
Chemical Patches	SPOTMYUV UV Sticker	Small	Low	No	Yes	Singular	Visual
Our System	**Hapt-Aid**	**Small**	**Low**	**Yes**	**Yes**	**Varied**	**Haptic**

Fig. 4. Comparison of Hapt-Aids with commercially available wearables for activity monitoring, including the Apple Watch [3], Fitbit [14], 3DFitBud [1], and SPOTMYUV [44]. Green denotes a desirable feature. Yellow and red represent a gradual decline in desirability. Please refer to appendix A for an extended comparison that builds upon this table.

a sensing source, without relying on specialized sensors [24, 33, 63, 73]. For example, Winkel et al. created a battery-free device that used the existence of harvested energy to identify user input [12]. Other exploitable energy sources include body motion [16], breath [11], and biochemical sources such as body heat [62] and sweat [32]. Seiko invented a watch that could harvest energy (self-winding) based on the user's arm movements [48], and the energy was solely used to power the visual watch face (no sensing). In other systems, harvested energy has been used as contextual sensing data include classifying gait [24], estimating calorie expenditure [72], monitoring light [28] and temperature [8], detecting hand gestures [4, 29], and detecting human activities [22, 47, 73]. In Hapt-Aids, we use accumulated energy to monitor activities that are coupled with the energy harvester through passive one-time sampling, significantly reducing power consumption. The energy from the harvester isn't used to power an external sensor — instead, this energy is a direct result of the activity that produced it, and therefore the energy amount itself can be used as a signal for activity monitoring. Though this comes with the trade-off of reduced sensing resolution (discussed in the Limitations Section 8), we identify applications for Hapt-Aids that can tolerate this ambiguity while still fulfilling user monitoring objectives.

2.2 Energy Harvesting for Haptics

Haptic actuation is an intuitive and perceivable modality, but it often struggles to be ubiquitous due to the need for relatively more power than LEDs or speakers. Prior research has proposed haptic devices that harvest energy from external energy sources, i.e. ultrasound [37] and laser beams [58], but these systems require significant environmental modification to be feasible. Luo et al. proposed fully passive haptics through soft textile wearables [31], which require no energy and instead utilize magnetic attraction to provide force feedback. Closer to our research is prior work that enables haptic experiences through active energy harvesting on-device [23, 52] rather than from external sources. Interactive Generator was the first self-powered device to provide haptic feedback, leveraging power generated from cranking the motor to apply force feedback using that motor [6]. Similarly, Shi et al. [53] utilized power harvested from a TENG to generate vibrotactile stimuli, and Teng et al. [61] harvested kinetic energy from arm movements in VR to enable a whole suite of haptic experiences. The Matrix PowerWatch [36] was a promising commercial smartwatch that was solar- and body heat-powered, and it could both count steps and transmit vibrotactile notifications. Unfortunately, the company stopped releasing updates in recent years and has since disbanded. Outside of these works, we found limited research showcasing standalone wearables harvesting energy that both monitored activities and delivered haptics. This is largely due to the high power demand of haptic actuators (e.g., power consumption of a sensor/MCU can be <0.5mW while a vibration motor requires >80mW), and the stricter form factor constraints of wearable energy harvesters, making it particularly challenging to implement self-powered, perceptible haptics.

2.3 Wearables for Activity Monitoring

There exists a large body of work on smart wearables for user wellness monitoring, the primary function of Hapt-Aids, but differing in form factor, power source, and functionality. We envision these technologies lying on the spectrum from passive to active wearables (Figure 2). On one end of the spectrum we place the basic Band-Aid, with no activity monitoring but with a simple, singular purpose, both inexpensive and easy to use. Many passive activity monitoring wearables exist near this end of the spectrum — for example, UV patches [44] and SPOTMYUV [56] stickers utilize passive material chemical properties that "monitor" ultraviolet (UV) light exposure, changing colors after the amount of UV passes a threshold. Battery-free wearable patches energized by external RF waves have also been proposed to measure physiological signals such as blood flow [9], and variations in wound fluid [65]. At the other end of the spectrum, we placed the familiar smartwatch. Significant efforts have been made to imbue these everyday wearables with an impressive set of monitoring capabilities, including an array of biometric and motion sensors found in smartwatches and fitness trackers [3]. However, these technologies can often be expensive and complex, with interfaces and setup procedures that can be difficult to navigate. Other types of complex activity monitoring wearables include common medical aids like insulin pumps for people with diabetes, which can monitor and administer insulin autonomously while stuck onto the body [55].

There are also many prior works focused on the middle of the spectrum, like ours, navigating the boundary of the simplicity vs. functionality tradeoff. These works explore ultra-low power and self-powered wearables that may have less activity monitoring capabilities, but are lower in cost and potentially eliminate the need for recharging batteries. For example, Sun Index is a solar-powered UV monitor [20], in contrast to the single-use UV patches that rely on passive chemical reactions. Other devices that integrate some digital components with some passive interactions include sweat sensing patches [39, 45, 78], ECG/EMG monitoring [26], and more [11]; see [17, 18] for a comprehensive review of smart skin adhesive patches for healthcare. Most of these devices, however, require the user's constant attention for notifications (e.g., LED light, screen) or rely on wireless connections (e.g., Bluetooth, WiFi) to convey activity information, creating friction in the user experience. RF Bandaid is one of the most closely related works, but differs from Hapt-Aids in multiple ways, including: (1) System Architecture: besides on-body sensors, the RF Bandaid system relies on external RF transmitter and receiver units to function. Conversely, Hapt-Aids are fully standalone wearable devices operating without any external device costs or installation overhead. (2) Energy Sources: RF Bandaid harvests energy from RF signals emitted by transmitters, meaning that a lack of RF energy (i.e., being too far from the RF transceiver) can lead to device dysfunction. In contrast, our system harvests energy directly from the activity being monitored. This constant coexistence of users, activities, and energy ensures that the device operates only when needed and is guaranteed to receive power when it requires power, enhancing the reliability of our system. (3) Sensing Logic: Hapt-Aids leverage the stored energy amount as sensing information, since it is coupled directly to the activity, while RF Bandaid uses specific sensors to perform sensing. (4) Applications: RF Bandaid demonstrated breathing, heart rate, temperature, and sound sensing applications, while our system presented a different and complementary set of applications. In general, Hapt-Aids move beyond visual/audio modalities by enabling haptic notifications while remaining self-powered, making them standalone activity monitoring devices. Figure 4 reviews the unique properties of our system that make it practical for wearable activity monitoring applications.

3 Design Considerations

We envision activity monitoring devices that users can wear and forget, offering unparalleled ease of use. The lightweight design and cost-effectiveness of these devices make them perfectly suited for monitoring simple physical activities and more generally accessible. Similar to the simplicity and convenience of applying a Band-Aid, these devices should be crafted to seamlessly integrate into the user's daily routine, providing hassle-free continuous monitoring without the need for user care (i.e., exchanging or recharging batteries, checking for notifications). Figure 3 shows several example use scenarios. We envision that users could easily get these Hapt-Aids from a local convenience store. After opening the protective wrapper, the device is deployed to an activity-mapped location on the body that can generate energy. A user can adjust the triggering activity amount by simply twisting a knob on the device. After the set activity amount is reached, the device vibrates to notify its user with an eyes-free notification. After use, the device can be recycled for future uses. To support these use scenarios, we designed a system following the design goals outlined below.

Maintenance-Free Instrumentation Our top-level design consideration was to make Hapt-Aids maintenance-free. This means that a user can put a Hapt-Aid on and not have to worry about maintaining it. The system should just work, without needing complicated setup, apps to download, or accounts to set up. To minimize device footprint, our system harvests energy and provides haptic actuation at the same body location. This requires a union of sensing, harvesting, and actuation to eliminate complex hardware and material instrumentation often featured in prior works as gloves, wristbands, sleeves, and exoskeletons [61]. To be "forgotten", a system must also be self-sufficient, able to harvest power for the entire system without requiring the user to constantly monitor its status (i.e., eliminating screens/visual output). This also means that a system can be placed outside line-of-sight body locations. We achieved this through numerous design factors, including identifying harvesters compatible with localized on-skin energy generation, making the tags self-powered to negate the need for recharging, and applying haptics as output so that users are not required to actively check the system.

Self-Powered & Energy Efficiency One of our biggest design goals was to make Hapt-Aids self-powered so that users do not have to worry about charging them. This allows us to cut down on complexity, cost, and user cognitive load for system maintenance, making Hapt-Aids easier to use. The lack of an active power source requires our system to be energy efficient, as energy harvesting typically does not generate as much power as batteries. Our design aims to efficiently convert all harvested energy into haptic signals. Unfortunately, many potential input energy harvesting methods do not generate much current, and often only generate intermittent charge. To increase energy efficiency of our system, we use only low-power, analog components in our circuit. We elected to not include microcontrollers or other digital elements on board, nor communication protocols, which reduces size and cost of our system. In our experiments, we measured sufficient harvested energy to support our self-powered operations.

Cost & Size Current smart wearables are often prohibitively expensive, and even cheap pedometers go for $15 at the lowest end. Our tags can be optimized to be cost-accessible for everyone, especially when the scale of mass manufacturing is introduced. Our simple system design cuts down on complexity, leading to a smaller footprint and reduced cost. We also eliminated the battery, which is typically one of the heaviest components. Other expensive and complex components include sensors and microprocessors. By removing all of these, the average overall cost of one Hapt-Aid is $11, or $3.60 without counting the cost of the energy harvesters. Additionally, the small analog circuits of Hapt-Aids are lightweight and easily wearable, so that they do not obstruct any movement or add any discomfort to the user. Hapt-Aids measure 2.6g without the energy harvesters, which are the heaviest components (~14.9g average). These can be made lighter with improved fabrication techniques.

4 Hapt-Aids Implementation

There are multiple approaches to creating a self-powered activity monitoring device with haptics, as shown in Figure 5: (A) Energy harvesters can act solely as power providers for the sensors, microcontroller units (MCU), and actuators. Integrated sensors create digital signals that are processed by the MCU, which would regulate haptic actuation [61]. (B) Energy harvesters provide power and sensing for the MCU and actuators. The MCU samples the energy signals to get sensory data that allows it to regulate actuation [6, 73]. (C) In Hapt-Aids,

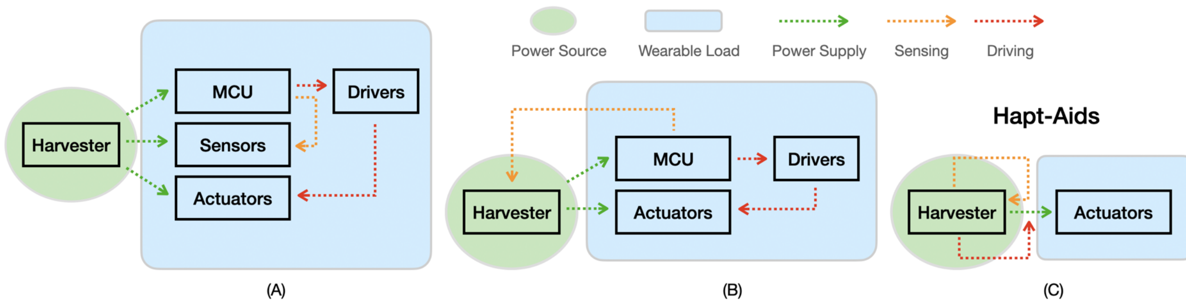

Fig. 5. Design options for self-powered activity monitoring device with haptic actuation. (A) Systems with energy harvesters, an MCU, and peripheral devices including sensors, drivers, and haptic actuators. (B) Systems with energy harvesters, an MCU that samples energy patterns for sensing (no peripheral sensors), drivers, and haptic actuators. (C) Our system (Hapt-Aids) utilizes analog components so that it has no peripheral sensors, drivers, or MCUs, only energy harvesters and actuators.

we propose a novel scheme in which energy harvesters provide power, sensing, and regulation directly to the actuators, where stored energy level acts as the sensory data and discharges directly as a haptic notification. This allows us to achieve a vision of a low-cost, self-powered, wearable device and removes the need for extra components. In the following sections, we justify our system design and demonstrate our proof-of-concept implementation optimized for our design considerations (Section 3).

4.1 Charging and Discharging Modeling

Prior related research on low-cost activity monitoring wearables typically used active power sources, like batteries, or entirely passive components. Our system design takes advantage of supercapacitors for their fast charging and discharging rates as well as the low leakage current, which is ideal for low-power energy harvesters and quick, high-energy haptic actuators. Here, we model the theoretical power characteristics of our system. This modeling indicates a one-to-one mapping between haptic actuation and target activity amount, tuned by a charge resistance potentiometer.

4.1.1 Charging. Our system uses harvested energy as sensing "data," so we model the charging process here to find the correlation between energy to and from key components of our system. We model the charging path as

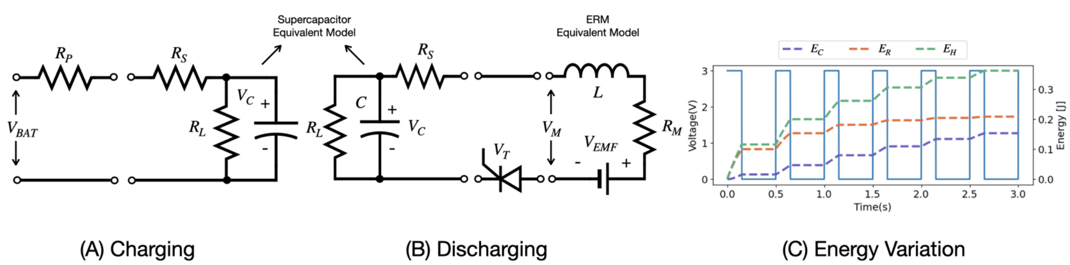

Fig. 6. Equivalent models of (A) charging and (B) discharging. R_P is resistance of the potentiometer. R_S and R_L are the equivalent series resistance and leakage resistance of the supercapacitor. The SCR triggers the discharging process at voltage V_T. R_M, L, and V_{EMF} are the resistance, inductance, and back EMF of the motor, respectively. The plot on the right (C) shows how the energy charged to the supercapacitor E_C increases approximately linearly with the number of input pulses.

an RC circuit. Most energy harvesters provide intermittent voltage outputs due to the kinetic characteristics of human motions, so we model the voltage source V_{BAT} as a periodic impulse signal. Given a conversion efficiency of α, the energy converted into electrical energy is $E_H = \alpha E$, where E denotes the energy from the user activity. While charging, the voltage in the supercapacitor is $V_C(t) = V_{\text{BAT}} \cdot \left(1 - e^{-\frac{t}{\tau_c}}\right)$, with a time constant $\tau_c = (R_p + R_s)C$. Since we use a supercapacitor for charging, the leakage resistance R_L is very large and thus negligible. The energy in the supercapacitor is $E_C(t) = \frac{1}{2}CV_C^2(t)$, which results in an increasing voltage across the supercapacitor as user activity continues. Equation 1 describes the energy dissipated by the potentiometer as a function of E_C when monitoring the activity energy E_C from $t = 0$ to $t = T$. We calculate the total energy, the energy stored in the capacitor, and the energy dissipated by the potentiometer using parameters from our component datasheets (detailed in Section 4.3). Figure 6C shows how the energy changes with time given the pulse input. The energy in the capacitor E_C is linearly proportional to the activity energy E_H. Increasing the series resistance results in greater energy dissipation and extends the time required for the capacitor to reach the trigger voltage.

$$E_H(T) = \underbrace{\int_0^T \frac{2E_C(t)}{C(1 - e^{\frac{t}{\tau_c}})^2 (R_P + R_S)} e^{-\frac{2t}{\tau_c}} dt}_{\text{Energy dissipated in } R_P \text{ and } R_S\text{: } E_R(T)} + E_C(T) \tag{1}$$

4.1.2 Discharging. Hapt-Aids use Silicon Controlled Rectifiers (SCR) to passively monitor and activate the discharging process (detailed in Section 4.3). Since back EMF of the motor V_{EMF} is dependent on the vibration load, which is difficult to model, we focus exclusively on analyzing the discharge process before and after the vibration. This provides valuable insights into the critical parameters necessary for designing Hapt-Aids. When the SCR is turned on, the supercapacitor begins discharging through the ERM motor circuit. Due to the inductor L, which opposes sudden changes in current, the current initially rises before gradually decreasing as the capacitor voltage drops, following the RL discharge dynamics described in Equation 2. The electromechanical model of the ERM motor states that $\tau = K_T I_M$ and $V_{EMF} = K_b \omega_M$, where K_T and K_b are constants, I_M is current through the motor driving its motion, and τ and w_M are torque and angular speed of the motor shaft. The current determines the motor's vibration output, while the back EMF is generated to oppose the input voltage. Before the motor starts vibrating, $V_{EMF} = 0$. To ensure that the motor can overcome the inertia and start vibrating, $I_M > I_{MS}$ and $V_M > V_{MS}$ has to be satisfied (I_{MS} and V_{MS} are the startup voltage and current of the motor which are obtained from the datasheet. $V_M = V_C - I_M R_S$). To decrease the startup time, we apply a higher voltage to overdrive the motor (e.g., using 2.8V to drive the 1.5V motor).

$$L\frac{dI(t)}{dt} + I(t)(R_S + R_M) + V_{EMF}(t) = V_C(t) \tag{2}$$

When the vibration motor stops vibrating, the energy in the capacitor keeps releasing until the SCR turns off ($V_{SCR} < V_{SCRH}$. V_{SCRH}: holding voltage of SCR, obtained from datasheet). For a given supercapacitor and motor, the time it takes to dissipate energy ($T_{dissipate}$) in the capacitor is determined by the V_{MS} and V_{SCRH} and approximated to Equation 3. We choose a vibration motor with V_{MS} and an SCR with similar holding voltage V_{SCRH} to shorten the SCR off-time. Once the SCR turns off, the system enters the next charging cycle. We compare this theoretical model with our experimental data in Section 5.

$$T_{dissipate} = -R_s C ln(\frac{V_{SCRH}}{V_{MS}}) \tag{3}$$

4.2 Compatible Energy Harvesters

Extensive work has explored, quantified, and implemented energy harvesters across application domains. Our devices uniquely identify wearable harvesters, coupled with user activity, that (1) uncover context through accumulative or maximum characteristics of the harvested energy and (2) operate unobtrusively, notifying users only when the activity exceeds certain thresholds. Figure 9 shows details about the harvesters we characterized, including both off-the-shelf and custom harvesters that meet our design criteria. We selected these energy harvesters for their proven ability to capture energy from activities that have demonstrated usefulness in prior applications [5, 8, 34, 62, 73, 76, 77]. Additionally, these harvesters convert activities into predictable continuous or intermittent voltage inputs, fitting the model outlined in the previous section.

4.3 PCB Design

Figure 7 provides an overview of our circuit. We designed a custom PCB (Figure 8) optimized as a 2-layer board so that it can be manufactured as a flexible PCB, with a surface area measuring 22×29mm and a thickness of 0.15mm without components and 5mm with. This flexible PCB brings us closer to our vision of an easily deployed wearable, because although the components are still rigid, the PCB itself can be deformed to sit atop the skin like a sticker or bandage (Figure 1). For the PCB schematics and other design files, please see our open source repository at https://github.com/FIGLAB/Hapt-Aids. The full parts list can be found on our Github – the total cost of each board comes out to be about $3.60, which would be majorly reduced with mass manufacturing.

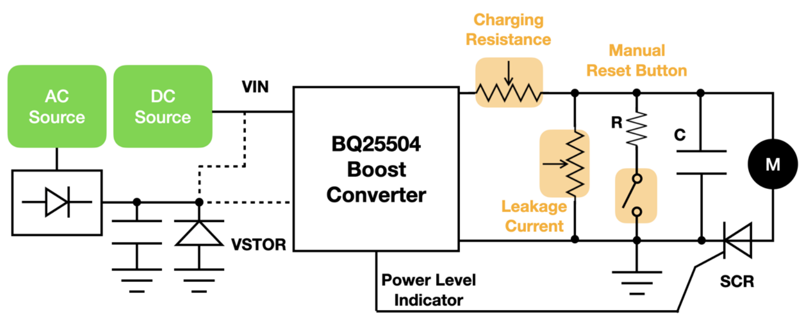

Fig. 7. A high-level overview of our entire system. For detailed implementation, see Figure 8.

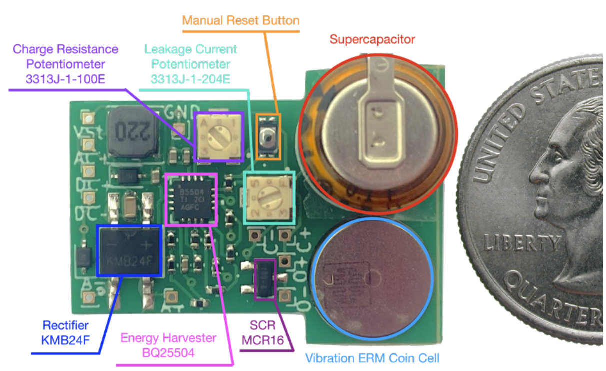

Fig. 8. Detailed shot of our custom PCB; we include a quarter for size comparison.

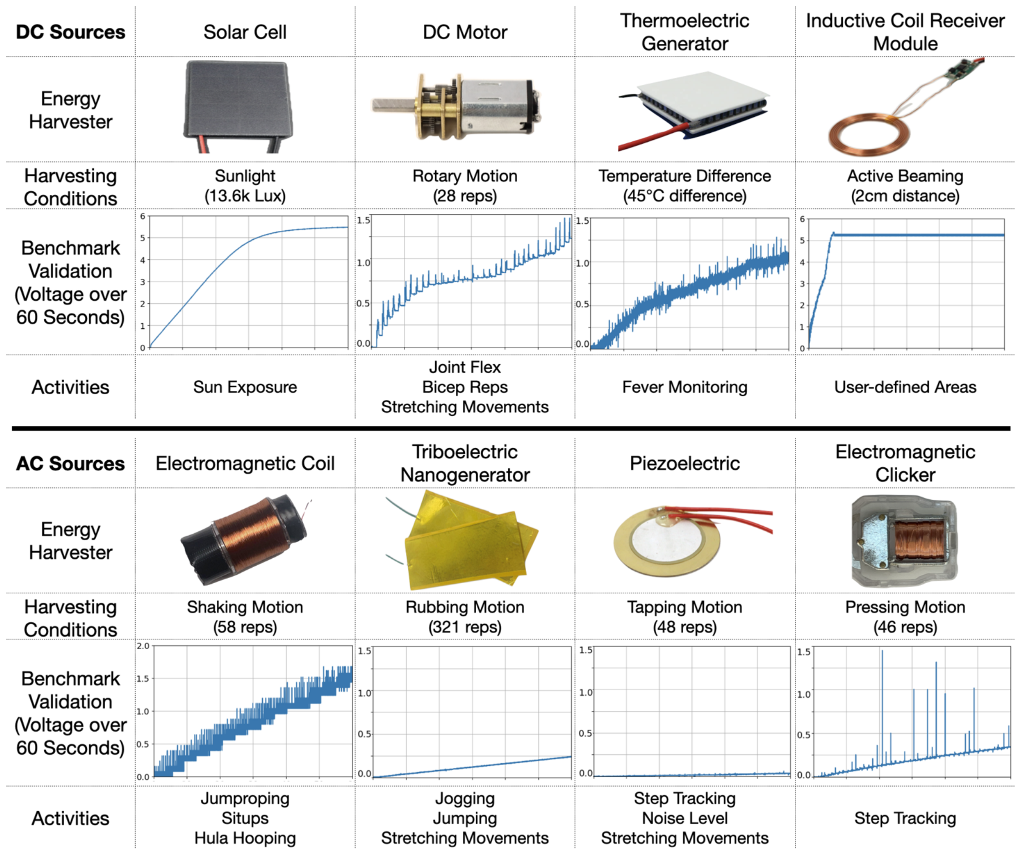

Fig. 9. Two tables detailing the energy harvesting inputs we tested; top table is DC sources and bottom table is AC sources. Harvesting Conditions are the evaluation conditions that correspond to the charge over time data in the Benchmark Validation row. To acquire this data, we connected the rectified harvesters to a 0.047F supercapacitor. We attached these harvesters to optimal locations on a user and repeated the associated activity, recording the number of repetitions while monitoring the capacitor's voltage over time. This allows us to visualize the distinct charging characteristics of different energy sources to inform our application design, and to evaluate the feasibility of these energy harvesters for Hapt-Aids.

4.3.1 Power Generation. Our design employs the popular energy harvesting integrated circuit (IC) BQ25504 for its efficient boost conversion, ultra-low start voltage, and built-in maximum power point tracker (MPPT) capabilities [21]. Our circuit features attachment points for both AC and DC energy sources. For AC energy sources, an ultra-low-forward-voltage rectifier bridge (Part #KMB24F) is used for AC-DC conversion. Low-voltage energy sources are fed directly into V_{IN} of the IC to boost the voltage. For high-voltage energy sources, we provide an option to charge the IC's internal capacitor directly.

4.3.2 Power Storage. The generated power is output from V_{BAT} and stored in a supercapacitor. Supercapacitors are ideal for applications that need both quick bursts of energy and moderate storage. An appropriate supercapacitor has a capacitance that is high enough to hold sufficient energy for haptics, but low enough to retain high power density, allowing for fast charging/discharging. For actuating a small vibratory haptic actuator (described in the next section, eccentric rotating mass motor #VC1034H025L, rated 1.5V, 35mA), we can calculate the capacitance based on adapted equations from our charge and discharge model (Section 4.1). We can rearrange the energy equation to calculate capacitance, with $C = \frac{2E}{V^2}$, where V is the motor voltage (1.5V) and E is the energy required. Energy is calculated by $E = P \times t$ where P is the power needed ($1.5V \times 0.035A = 0.0525W$) and t = discharge time, which needs to be a couple of seconds for a short haptic notification. Plugging that back in, $C = \frac{2\times 0.0525\times t}{1.5^2}, t \approx 2s \Rightarrow C = 0.0933F$. We evaluate supercapacitors with common capacitance values that are closest to this calculated value (i.e., $C = 0.022F, 0.047F, 0.1F, 0.47F$) in Section 5.

A silicon-controlled rectifier (SCR, Part #MCR16) is used to latch the power within the supercapacitor during the charging process. The built-in power level indicator V_{BATOK} outputs a pulse signal when the voltage in the supercapacitor reaches a threshold (2.75V in our design). This pulse signal feeds to the gate pin of the SCR, triggering the discharge process when the gate voltage reaches the threshold. This trigger eliminates the need for constant regulation from voltage/current sensing and digital ICs, which require higher power consumption and cost but can provide more precise discharge control.

4.3.3 Haptic Output. We use an Eccentric Rotating Mass (ERM) vibration motor (Part #VC1034H025L, rated 1.5V, 35mA) for haptic output, given its popularity as a simple vibration haptic actuator. We chose this specific actuator for its low power characteristics, and we validate that the signal is strong enough for human perception in Section 5. After the pulse signal is applied, the SCR turns on and opens a path for the supercapacitor to release its energy to the output actuator. The motor keeps vibrating until the voltage in the supercapacitor drops below the operating voltage/current of the ERM motor. The energy continues to be released until the SCR drops below its holding voltage and current, at which point the SCR turns off, and the circuit begins the next charging cycle.

4.3.4 System Validation. We validated the Hapt-Aid system's capability of storing energy in the supercapacitor until reaching the release threshold, after which the energy is output to the vibration motor. Considering the diversity of voltages and currents generated by different harvesters and their environmental variations, we tested different levels of voltage and current at the input terminals of our board. Specifically, we used a DC power supply to step the input voltage from 0.5V to 4V with a maximum current of 20mA, and then held the voltage at 3V and stepped the current from 5mA to 30mA. The validation criteria are based on the known voltage and current level of small, wearable energy harvesters (e.g., solar panel ≤10mA, DC motor ≤30mA). We placed a vibration sensor beneath the ERM motor to monitor the vibration effect. Note that this vibration sensor is electrically isolated from our board and used for validating the vibration of the motor. An example of the voltage in the capacitor with 3V, 10mA input is shown in Figure 10A, from which we can observe the charging, discharging, and vibration output. Under each of the aforementioned conditions, we measured the time required to activate the vibration motor, recorded the power delivery values from the DC power supply, and noted the voltage across the supercapacitor at the moment of activation. We then calculated the device's power consumption (i.e., DC supply power minus the average charging rate of the supercapacitor) and energy conversion efficiency (i.e., the ratio of energy stored in the supercapacitor to the energy supplied by the DC power supply). Figure 10B and C present these results. On average, our system has an energy conversion efficiency of 35.77% (SD=5.75) and power consumption of 21.28mW (SD=14.32). Note that our system uses a "power-as-you-go" method, which is different than prior works relying on constant power, and thus power consumption should not be used as the only comparison metric. In certain scenarios where intensive activities are expected to be monitored (i.e., strong sun exposure and frequent movement), our system would receive a lot of power, which would manifest as high power consumption. In scenarios where activities are sparse, our system would receive very little power but still be able to operate, resulting in a very low power consumption. Nonetheless, to draw comparisons with power consumption of prior systems, we measured our power consumption under various energy scenarios. Additionally, we calculate energy conversion efficiency across these energy scenarios, to gain additional insights into our system's performance.

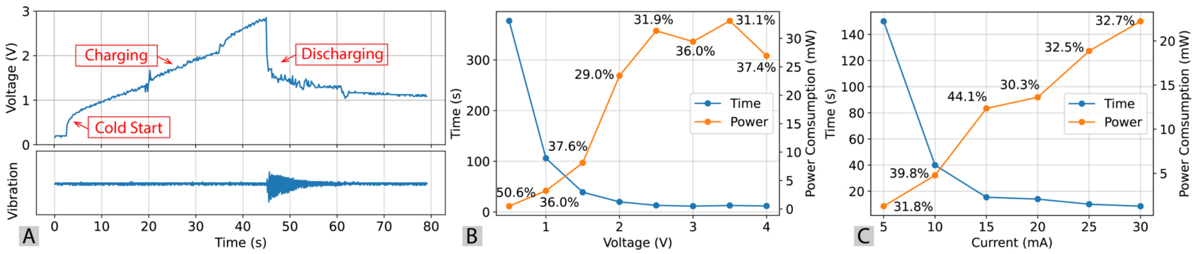

Fig. 10. System validation results. (A) top shows an example capacitor charging curve with 3V, 10mA input, while bottom shows the corresponding vibration magnitude measured by the vibration sensor. The right two plots show the charging duration, power consumption, and power efficiency with different input voltages (B) and currents (C). The % number next to each data point of the orange curve is the energy conversion efficiency at the corresponding condition.

4.3.5 System Tunability.

Along with compatibility with various energy sources, we incorporated several modifiable factors to tune individual Hapt-Aids; we envision these being adjusted on either the manufacturer or user side. Section 4.1 modeled key parameters in the charging and discharging process. Below, we explain how our device provides customizability with no digital components.

Haptic Intensity and Duration. As described in Section 4.1, haptic intensity (I_M) and duration (t_M) of a haptic actuator are determined by the characteristics of the supercapacitor (C, R_S) and the voltage threshold of the power level indicator (V_T). Therefore, the supercapacitor can be swapped for different haptic output characteristics; for example, we use a smaller supercapacitor in the user study, making the charge time of the Hapt-Aid shorter for our time-constrained user study. We quantify how user perception of haptic intensity and the output vibration duration changes with the supercapacitor in Section 5.

Activity Monitoring Threshold. In Equation 1, increasing R_P requires more energy harvested from the activity to charge the supercapacitor to the threshold. In our system, R_P corresponds to a potentiometer (Part #3313J-1-100E, 10Ω standard resistance) that is in series with the charge output of the IC. The resistance introduced by this component dissipates excess energy going to the supercapacitor: the higher the resistance, the more energy that is dissipated, meaning that it will take more activity energy to charge the supercapacitor to reach the triggering voltage level. This allows Hapt-Aids to have adjustable activity amounts per user needs.

Excess Energy Dissipation. Hapt-Aids can also automatically reset when necessary. For example, sun exposure monitoring is only concerned with exceeding a safety threshold within a specific amount of time, or step trackers may want to reset to 0 steps overnight. To accomplish this, our system has an optional potentiometer (Part #3313J-1-204E, 200kΩ standard resistance) across the terminals of the capacitor that explicitly introduces a leakage current, acting as a "reset" mechanism for the Hapt-Aid system. We also added a manual reset button so that the user can also manually discharge the supercapacitor and "restart" the Hapt-Aid at any time. This button shorts the terminals of the supercapacitor across a 100Ω resistor that causes rapid energy dissipation.

5 Tuning for Optimal Configuration with User Perception Evaluation

Following ethics review and approval, we conducted three studies to evaluate haptic output and user perception. We emphasize that these are not haptics studies as in prior work to evaluate user experience [10, 25, 41], but instead to find the parameters of the system that would be suitable for user notification. Specifically, we aim to answer the following questions:

- Q1: What is the minimum amount of energy needed for our vibration motor to render noticeable haptic feedback?
- Q2: How does the discharge behavior of supercapacitors vary with different initial voltage and energy levels?
- Q3: Are optimal configurations sufficient in rendering haptic feedback noticeable at target Hapt-Aid locations, and while the user is preoccupied with activity?

Power Storage Parameters and Discharge Behavior The goal of this study was to *evaluate appropriate power storage parameters* for Hapt-Aids and *validate the discharging behavior* with experimental data. We recruited 5 participants (mean age=25.2, 3 identified as male and 2 identified as female). We charged the capacitors with a DC power supply, then used a button to release the charge to our ERM vibration motor. This motor was placed on the user's upper bicep, secured with a 0.75×3 inch bandage. The user was instructed to look away from the setup and to signal when they felt a haptic vibration. Then, they were instructed to report whether the haptic feedback was perceivable, and rate the strength of the haptics on a scale from 0 (did not feel anything) to 10 (strongest sensation). We tested 4 different supercapacitors, with capacitances of 0.022F, 0.047F, 0.1F, and 0.47F (see Section 4.3.2 for supercapacitor criteria). We used 5 different voltages (1V, 1.5V, 2V, 2.5V, and 3V) leading to 20 combinations total, which we presented in random order. Finally, we also measured the time it took for each combination to discharge down to 0.5V.

The perception ratios (i.e., number of perceived haptic trials / total number of trials) were 0/5, 0/5, 4/5, and 3/5 at 1V, and 5/5, 3/5, 3/5, 5/5 at 1.5V for 0.022F, 0.047F, 0.1F, and 0.47F supercapacitors, respectively. With voltage above 1.5V, all induced vibrations were perceivable. Figure 11, left shows these results. The minimum energy needed to actuate the motor for rendering noticeable haptic feedback was 23.5mJ (Q1). Additionally, we found that the measured correlations between charged voltage and vibration motor activation time closely aligned with those predicted by our model (Q2). We observed that although the 0.022F capacitor can produce perceivable vibrations, the duration is too short (<1.5s), while the 0.47F capacitor generates strong vibrations with excessively long durations (>30s). This informed our design choice of using the 0.047F supercapacitors for the appropriate strength and duration of haptics, though the other supercapacitors can be used depending on desired haptic output. We also calculated the theoretical discharging time using Equation 3, and compared it with the measured discharging time to validate our model, as seen in Figure 11, middle. The discrepancy between the measured and calculated time comes from the varying resistances and inductances of the vibration motors, which we did not consider in our model.

Perception of Haptics at Different Skin Locations during User Distraction With the appropriate power storage parameters chosen (voltage and supercapacitor), we conducted a user study *perception test* at a variety of *target locations* while participants were *distracted*. Specifically, we chose four key locations that would be likely

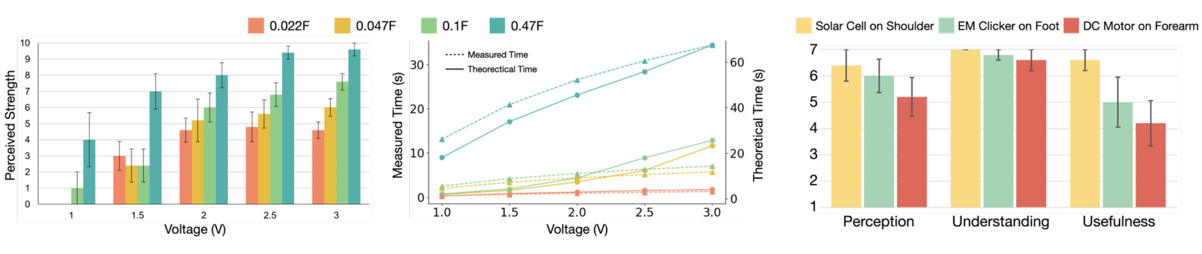

Fig. 11. Results from the haptic perception studies. Left: average user-rated perceived strength for different combinations of charge and capacitance. Middle: comparisons of output vibration duration between our experimental data and the theoretical model (Sec 4.1). Right: perception, understanding, and usefulness of example Hapt-Aid prototypes in three key locations.

application areas for our Hapt-Aids: the back of the shoulder, the waist, and back of the foot/above the heel, all on the side of the dominant hand. We sought to evaluate whether users can easily perceive haptic feedback at these locations under different distraction conditions, both mental and physical. In the mental distraction scenario, participants were told to listen to music, talk, and scroll their phones while remaining physically still. In the physical distraction scenario, participants were made to do corresponding active tasks based on the appropriate limb: fold clothes or stack dishes for the arm and shoulder, and walk around for the waist and foot. Participants were also mentally distracted during these tasks, as they were either preoccupied with thinking about the task or were using their phones while walking around.

For this study, we recruited 10 participants (mean age=28.2, 7 identified as male and 3 identified as female). We used a 0.047F supercapacitor, as informed by the previous study, and the same ERM vibration motor was adhered to the participant using a bandage. The cap was continuously charged by battery and then discharged at random times while the participant was distracted. If the participant perceived the vibration, they would either raise their hand or verbally confirm the haptic notification. This was repeated 10 times for each distraction condition for each location, totaling 100 times per distraction condition per location. All participants had 100% accuracy of perceiving the vibration while mentally distracted. While physically distracted, the shoulder had 96% accuracy, the arm had 97%, the waist had 98%, and the foot had 98%. The high accuracy numbers of these results validate that the haptic notification is easily perceivable while users are in both mentally and physically distracted conditions.

Perception of Hapt-Aids during User Activities The goal of this study was to validate that Hapt-Aid notifications could be perceived at *key locations* on the body *while the target activity was occurring*, and that the notifications *conveyed appropriate information*. This also helped us evaluate the feasibility of potential example applications as *usable systems*. We created prototype versions of experimental Hapt-Aids, modified so that the haptics would trigger faster (using larger and more efficient energy harvesters and precharging the capacitors). We note that this is not an evaluation of the system, only of user perception - we present an end-to-end system validation user study in Section 7.

For this study, we recruited 5 participants (mean age=26.8, 3 identified as male and 2 identified as female). Participants tested every device individually, with the presentation order randomized. A solar cell Hapt-Aid was adhered to their upper left shoulder with a bandage, and they went outside and walked around while surfing their phones. An EM clicker Hapt-Aid was placed on a slipper for easy reuse, and participants did laps around the lab while browsing their phones and listening to music. Finally, a DC motor Hapt-Aid was fitted to their right arms with straps, and participants did bicep curls with no weight. After using each device, participants filled out a survey with three statements:

(1) I felt the haptic notification. (*Perception*)
(2) I understood immediately why the notification occurred. (*Understanding*)
(3) If this were a commercial product the size and cost of a bandage, I could see myself using it. (*Usefulness*)

Note that the parenthesized keyword was not visible to the user, but is used here to denote the metric that experimenters were evaluating with each statement. These statements were answered on a seven-point Likert scale (1-strongly disagree, 2-disagree, 3-somewhat disagree, 4-neither agree nor disagree, 5-somewhat agree, 6-agree, 7-strongly agree).

Results from the user study are summarized in Figure 11, right. The solar cell location & activity was the most perceptible, but all systems scored well on perception. This validates that haptic notifications are perceptible on key locations during activity, even while users are not actively paying attention to the Hapt-Aid (Q3). We hypothesize that the reason the forearm DC motor was perceived the least strongly was due to the movement of the prototype band on the participants' arm, creating distracting stimuli. Across all devices, participants strongly agreed that they could immediately understand the meaning of the haptic notifications, indicating that Hapt-Aids can convey activity information to users regardless of attention level. Finally, participants ranked the solar cell Hapt-Aid to be the most useful, with multiple participants verbally emphasizing their interest in a passive solar monitor (*"I really liked the sun exposure one, I feel like I'd use that all the time."* -P4). We used this information to inform our development of our final example applications.

6 Example Applications

We implemented four versions of our system using a subset of applicable energy harvesters with characteristic energy profiles, demonstrating the compatibility of our system across diverse applications. We chose to implement these specific harvesters based on 1) which associated activities we felt were most desirable to monitor and 2) which had the most likely chance of success over a realistic activity duration. For instance, mid-efficiency triboelectric generators can be easily fabricated using everyday materials. However, they generate energy too slowly and require an impractically high level of activity to sufficiently charge the supercapacitor. Instead, we selected an electromagnetic clicker as our testing harvester, as it is in the class of energy harvesters that produce intermittent impulses (e.g., piezoelectric, electromagnetic coil). For harvesters that output constant directional current (e.g., thermoelectric generator), we selected a solar cell as our testing harvester. We also selected a DC motor, as its wavy energy profile represents an intermediate case between constant output and intermittent output harvesters. These three harvesters (electromagnetic clicker, solar cell, DC motor) utilize energy harvested from user activities, which we propose as the main use case of Hapt-Aids. We also created an additional application with our system featuring an inductive coil that receives energy actively delivered by inductive transmitters deployed in the environment, triggered by user proximity to an object or location. We implement this device to demonstrate our applicability for this complementary use case. All of these Hapt-Aids used a 0.047F supercapacitor for energy storage. Together, these applications explore the design space of Hapt-Aids as a generalized, light-weight form factor for activity monitoring – please see our Video Figure for demonstrations. We also evaluated end-to-end deployment of these applications in a user study (Section 7) to validate feasibility in real-world use.

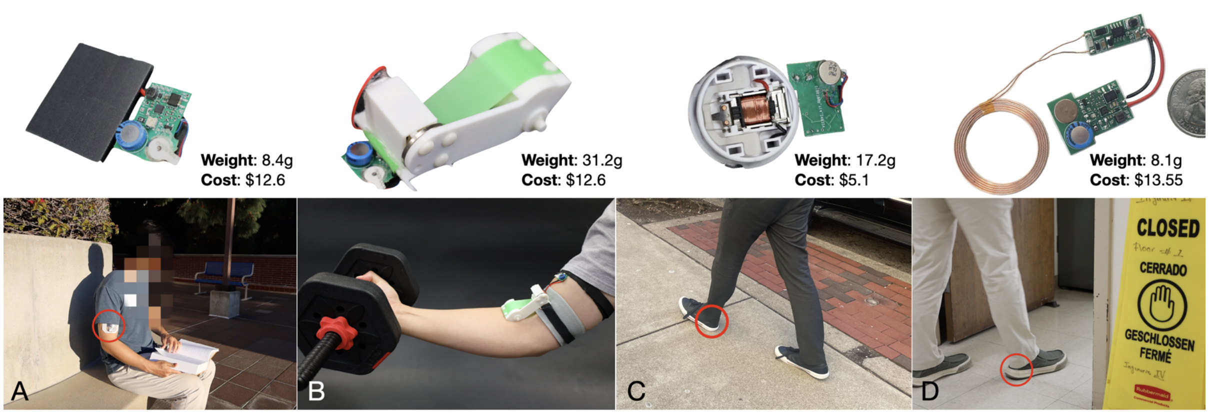

Fig. 12. Users wearing our Hapt-Aids while performing the associated activities, with a zoomed-in version of the Hapt-Aid above. (A) Sun exposure monitor on the arm as the user reads outside. (B) Bicep rep monitor on the elbow joint to keep track of the user's bicep curls. (C) Step tracker attached to the user's foot as they walk down the street. (D) Active energy harvester attached to the user's foot, notifying them as they enter a closed area.

6.1 Sun Exposure Monitor

This device monitors a user's recommended amount of sun exposure, notifying them when the threshold has been exceeded and it is time to seek shade. We envision this form factor being attached anywhere on the body or clothing that is exposed to the sun (Figure 12A). For the harvester, we used the AnySolar Part # SM141K10LV measuring 45×36×0.3mm, weighing 5.8g, and costing $9. Note that our device is compatible with various solar cells, including the AnySolar Part # KXOB25 ($2.42) seen in Figure 1, with the choice depending on desired sun exposure measuring level. Therefore, our device is not limited to any specific sun exposure durations, but depends on the solar cell response.

6.2 Bicep Rep Monitor

This example device monitors rotational movements on a user's body, which we deploy on the joint of the elbow (Figure 12B). Flexing the arm rotates the DC motor and generates power, which is a minimalist design inspired by Teng et al. [61]. After the bicep rep activity level is achieved, the device notifies the user to take a break. We used a 200RPM DC geared motor for its compact size (16×12×10mm) and reasonable torque and voltage output (3V no load). We 3D printed a mechanism to couple arm flex motion with rotation of the motor shaft, and used an elastic strip to allow the mechanism to slide along the arm. The size of the whole device is 48×81×35mm. The overall cost is $9 and the weight is 28.6g, with a maximum output voltage of 4.2V when a user flexes their arm fully.

6.3 Step Tracker

This device tracks steps, with each step impacting and deforming an electromagnetic clicker (Part #TEL0146, $8) to generate a voltage spike. For this device, tuning the charge resistance potentiometer to higher resistance effectively sets the step threshold higher, as more steps will be needed to charge the supercapacitor. This emulates a common smartwatch function, where the watch buzzes when the user reaches a step amount. We utilized a microgenerator from a commercial self-powered switch and integrated it into a shoe insole (Figure 12D); the buzz is felt on the feet. This low-profile harvester has a thickness of 7.7mm, an area of 17×33mm, weighs 14.6g, and has a one-step open circuit voltage output of 28V, connected to AC input voltage.

6.4 Explicit Energy Transfer

The location of a person has a strong correlation with their activity, and the person can benefit from knowing if their location poses any risks (e.g., monitoring their exposure in a hazardous area). We believe this system could be used for accessibility to supplement visual- or hearing-impaired people with haptic feedback, and we utilized an active energy source rather than harvesting from user kinetic energy. An inductive coil on the user's foot receives energy transmitted wirelessly when the user steps on a tile embedded with a transmitter. We used an off-the-shelf inductive coil set consisting of a 9V transmitter coil and a receiver coil with 5V DC output [2]. We placed the 38×38mm receiver, weighing 5.5g, under the user's heel. The transmitter was powered by a 9V power supply, and the haptic effect can be tuned to trigger almost instantaneously when a user steps on the transmitter-embedded tile.

7 User Study

7.1 In-Lab, Short-Term Study

7.1.1 Procedure. Following ethics review and approval for our study, we recruited a user pool of 20 participants in total (mean age 25.8, 5 identified as female and 15 identified as male) who were compensated $20 for our one-hour study. Each Hapt-Aid device shown in Figure 12 was evaluated by 10 participants from this user pool. Before wearing each Hapt-Aid, a brief description of its intended use was provided to prepare the participant.

The participant performed the device's corresponding activity until receiving a haptic notification, and repeated this three times. Each application had a slightly different procedure, as described next.

Sun exposure monitor: After a Hapt-Aid was adhered to their arm, the participant was instructed to idle outside by walking around and browsing on their phone (to avoid focusing too much on the Hapt-Aid). When the participant felt the haptic notification, the experimenter recorded the duration of sun exposure (in seconds) and the environmental conditions by measuring light intensity in four directions using a digital handheld illuminance meter [64]. We note that the actual sun exposure received by the Hapt-Aid differs from the environmental illumination based on the participant's body movements. However, we could not obtain a continuously accurate sun exposure reading because the meter was too bulky and heavy to attach to participants, and would restrict their natural activities.

Bicep reps monitor: A Hapt-Aid was adhered to a strap to facilitate reuse, and was fastened near the participant's elbow. Participants performed bicep curls without a dumbbell, and the experimenter recorded the number of reps when the vibration was felt. Participants did not receive any instructions on how to bend their arm, such as the speed or range of motion.

Step tracker: Our Hapt-Aid was integrated into a slipper to facilitate reuse, and the haptic actuator and Hapt-Aid retained direct contact with the participant's foot. Participants wore the slipper and walked on a treadmill at their normal pace. A 3DFitBud step counter [1] was clipped to their thigh as ground truth. Upon sensing the vibration, they stopped walking, and the experimenter recorded the step count and treadmill distance.

Active energy transfer: This Hapt-Aid was also integrated into a slipper to facilitate reuse, directly contacting the participant's foot. The user walked towards and stepped on a 3.5mm square of foam board with the active energy source embedded. The experimenter started the timer once the participant's foot was in contact with the transmitter-embedded tile, and recorded the duration until the participant felt the haptic notification.

7.1.2 Results. The results can be seen in Figure 13. For sun exposure, the notification triggered on average after 24.46 (SD=8.76) seconds of sun exposure under a light intensity of 26.83 (SD=10.33) kLux. As shown in Figure 13 A, the time it takes to generate haptic notification decreases as light intensity increases, as the Hapt-Aid was exposed to more sunlight and therefore charged in less time. We observed variability in the time it takes to generate haptic notifications across the three trials per participant, likely due to differences in sunlight exposure during activities. Since we did not restrict participants' body positioning or movements, the average light intensity serves only as an estimate of actual exposure. Nonetheless, the correlation between light intensity and average time to haptic notification suggests that Hapt-Aids can effectively monitor sunlight energy amount during exposure.

For bicep reps, the haptic notification was triggered after an average of 110.43 reps (SD=49.48). Our results indicate that the device harvested an average of 1.67mJ per rep (SD=0.52). This device exhibited greater variation compared to others, likely due to differences in participants' speed and range of motion during reps. We

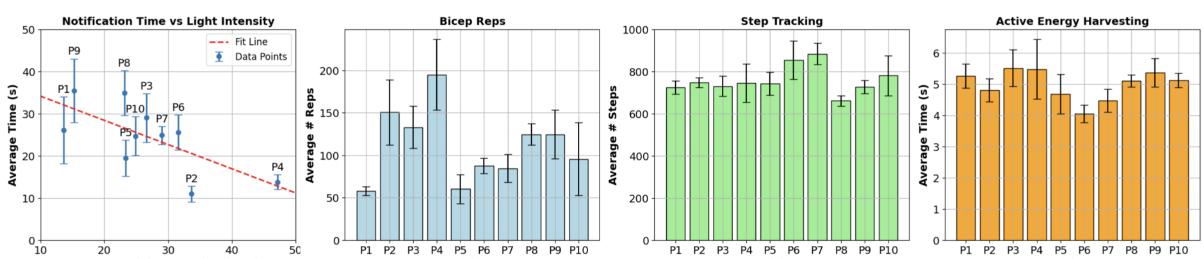

Fig. 13. User study results for A) sun exposure monitor, B) bicep reps monitor, C) step tracker, and D) active energy transfer.

hypothesize that, based on the principle of energy conservation, the energy stored in the supercapacitor closely approximates the energy captured by the harvester, which could be a more accurate reflection of user exertion than numerical rep count.

For step tracking, we measured an average of 759.03 (SD=80.36) steps and 0.45km (SD=0.08) to trigger the vibration. On average, our device harvested 225.71uJ (SD=21.52) energy per footstep. As illustrated in Figure 13C, results show greater consistency in the number of steps across participants due to the minimal variation in power generated per step with our clicker harvester, regardless of walking kinetics (i.e., weight and gait). This result suggests a potential design space for harvesters where activity count is prioritized over energy exertion, enabling relevant health applications such as medication reminders.

Finally, for active energy harvesting, we measured an average of 4.98 (SD=0.62) seconds until the Hapt-Aid triggered. This device was designed to have near-instantaneous haptic notifications, for hazardous area warnings or accessibility applications. However, this system can be tuned to accumulate energy at a slower rate by choosing a larger resistance value for the tuning potentiometer, setting an alert for longer-duration activities like tracking work hours.

7.2 In-the-Wild, Long-Term Study

This study explores the usability of our device with users through the *calibration process* and *long-term use*. We chose our solar exposure monitor as a representative example in this study. We envision that manufacturers can calibrate the triggering activity threshold to a fixed level at the factory under controlled settings. At the same time, with the help of a simple calibration guide, Hapt-Aid users can also quickly customize the device to suit their individual needs. These two types of calibrations, similar to those found in commercial products, allow for flexible and more accurate device usage.

7.2.1 Device Calibration. Our device calibration is based on the following information and assumption: (1) According to the research in [19], UVB (290–320nm) and UVA radiation (320–400nm) are the two primary components of the solar spectrum that are harmful to the skin, and the average daily UVB dose (without use of sunscreen) to maintain healthy skin is $10.96mJ/cm^2$ (2) UVB makes up 0.3-0.5% of the total solar energy (we used 0.5% for our calibration), and 5% of the UVA+B radiation. We selected a solar cell with the following criteria: (1) an area of $1.84cm^2$ and a 25% efficiency measured under standard solar conditions of $100W/cm^2$. (2) energy absorption wavelengths ranging from $300nm$ to $1100nm$, which is 70%-75% of the total solar energy (we used 70% for our calibration). This means we can estimate that the maximum electrical energy generated by the solar cell when the user is exposed to the maximum allowable UV dose is $E_H = \frac{10.96}{0.5\%} \times 70\% \times 1.84 \times 25\% = 705mJ$. This is sufficient energy to power our device for perceivable haptics (minimum $178mJ$) while providing leeway for users to adjust the sensitivity as needed.

We calibrated our device by calculating the corresponding UV dose at each potentiometer resistance. Specifically, at different potentiometer positions, we measured the UV radiation with a UVA+B light meter (unit: $\mu W/cm^2$), recorded the time needed to generate a vibration, and then calculated the UV dose by multiplying the two values. For UV radiation, we recorded two measurements when our device was first exposed to sunlight and at the onset of the resulting haptic notification, and used their average to approximate the UV radiation during that period. Figure 14 shows the results of these calculations, from which we found three adjusting levels for a user to select from: low (32%), moderate (65%), and high (94%). These three levels indicate that the device will deliver a haptic notification when it measures an approximate 32%, 65%, and 94% of the daily limit of UV dose. We envision that these calibration calculations would be performed solely by the manufacturer prior to use, so that users need only to perform a simple turn of a knob to select the desired UV dose.

7.2.2 Procedure. We recruited 8 participants (mean age=27.3, 4 identified as male and 4 identified as female) for this study, which was approved by IRB at our institute. Before the study, we introduced the device to our participants, and instructed them to calibrate the device to the sensitivity per their needs (i.e., by adjusting the potentiometer). Participants attached the device on their body at a location of their choice using an adhesive patch. Then, the participants left the lab and performed their own routine activities for four hours. Afterwards, participants returned to the lab and evaluated the usability of our device by filling out the Standard Usability Scale survey [7]. We also conducted a 5-minute semi-structured interview, starting with the participant outlining their activities during the study, followed by the following questions:
(1) How did the device feel throughout the day? Was it comfortable to wear?
(2) Did you clearly notice the vibration alerts when they occurred?
(3) Was the calibration process easy to understand and follow?
(4) Do you trust that the device is functioning properly and why?

7.3 Results

Six participants attached the device to their hands, one to their leg, and one to their arm. Figure 14 shows the average adjusted SUS scale evaluated by participants. Overall, our device had a mean SUS score of 91.25 out of 100. All participants reported that they could clearly feel the vibration and were almost unaware of the device's presence most of the time, unless it vibrated, or it scratched objects nearby. P3 commented *"It's easy to use and interesting. It was comfortable. I forgot its existence most of the time."* When activated, however, P4 said that *"the vibration is hard to ignore."*

Participants found the calibration straightforward, but also suggested adding clear indicators like arrows and colors to the potentiometer to make it easier to understand. Four participants preferred to be notified at 65% sun exposure, with P6 commenting *"I hope it's around 60–80%, somewhere in the middle, so I have enough time to respond before hitting the limit, but it doesn't alert me too early."* Two participants set the exposure amount at 32% as they wished to take early preventative action, with P4 saying *"I usually get sunburned, and it's quite painful, so I really want to take action immediately."* Finally, two participants set the calibration to 94% with P3 noting that *"Personally I love sunlight and I don't want the vibration to be too frequent."* This variation among users suggested that a certain tunability on the device is essential to adapt to different needs. Participants also indicated that they trusted the device even without a vitality interface. P2 mentioned that *"I trust the device is*

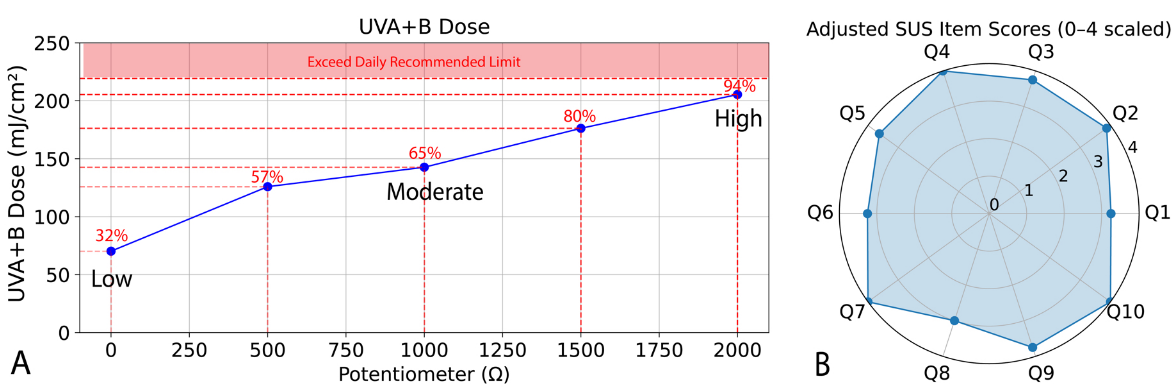

Fig. 14. A) Measurement of UV dose varying with potentiometer, serving as a reference for user calibration. B) Radar chart with the average adjusted SUS scores response to each of the 10 SUS survey questions [7].

functioning because it vibrates when I'm out in the sun and stays quiet when I'm not. That's why I believe that it is working well.". However, participants also suggested that indicators confirming the device's functionality would be helpful. Specifically, P1 noted that *"An LED would let me know that the device is functioning."* Additionally, P2 suggested *"I would like a subtle notification when I'm under low sunlight exposure, around 10% of the limit, to confirm the device is functioning, and a strong notification when I reach 90% of the limit."*

8 Discussion and Limitations

8.1 Form Factor

As wearables become increasingly ubiquitous, the demand for being thinner, smaller, lighter, and softer increases, making them more comfortable to wear. This increasing comfort helps the technology disappear into the background of the user's life, as these non-intrusive form factors are more easily forgotten about. While Hapt-Aids push towards this goal of maintenance-free with small-footprint, flexible PCBs, there are still many optimizations that can improve our system. In the future, we can see our designs being integrated into soft materials such as textiles and hydrogels, borrowing from prior research in the soft wearables field [35, 67, 68, 71]. This would also allow our wearables to take on slightly different form factors, like being integrated in clothes or on-skin patches. These potential modifications, as well as optimizing the design of Hapt-Aids as bandages or wearables, can improve the comfort of the devices in future work.

Outside of becoming more "soft," more can be done to either replace the rigid circuit components we have on Hapt-Aids with flexible ones, or minimize the physical size. For example, borrowing from advanced materials science research that hasn't reached consumer mainstream, future Hapt-Aids can have thin-film supercapacitors [74] directly integrated, drastically reducing the thickness of the overall Hapt-Aids. Similarly, smaller ERM vibration motors do exist, although requiring higher power consumption than the ones we are using. As these get more optimized, future Hapt-Aids can further reduce thickness by switching to other ERMs that fit the power profile our system provides.

Our Hapt-Aids applications were not efficiently maximized for cost, as they are prototype demonstrations of the technology and system instead. Therefore, they do not represent the lowest achievable cost of manufacturing Hapt-Aid devices in bulk: for example, the cheapest commercially available and compatible solar cells (e.g., under 30 mW) were $1.76 at bulk scale, reducing the overall cost of Hapt-Aid to less than $5 (the solar bandaid in the hero figure is around $6). Although this is more expensive than a single-use UV patch (typically less than $1), our reusable device becomes cost-effective with re-use and offers more functionality than the UV patch (e.g., different applications enabled with same architecture, haptic notification). Compared to smart UV monitors (e.g., $59.99 for My Skin Track UV listed in [17], and $49.99 for SunFriend found in Table 15), our device is 10 times less expensive, while still offering the usability benefits introduced by the new architecture (e.g., battery-free, haptic notification). On average, harvesters (not including our board) account for 67.27% of the total cost of our system. Among our examples, solar cells are currently the cheapest, likely due to their intensive optimization for large-scale manufacturing. Thus, we believe it can be an indicator of future cost trends for other harvesters given sufficient optimization for wearable applications, which would further lower the cost of our system.

8.2 Application Scope

We envision Hapt-Aids to be compatible with a wide variety of energy harvesters, enabling a broad range of applications. For example, a soft piezoelectric generator could be attached to the throat to monitor food intake or integrated into earrings to monitor noise levels and provide timely notifications; a sweat harvester could be used to monitor hydration levels or electrolyte balance during exercises, offering real-time feedback to users; a thermoelectric generator could be used for fever monitoring or integrated into a finger probe to provide alerts when approaching a heat source. Active energy transfer could be integrated anywhere in the environment to notify users of potential hazards, such as machinery with moving parts, high-temperature surfaces, or restricted areas, providing immediate feedback to enhance user safety. The biggest challenge of implementing all of these applications directly in our research was the inefficiency or lack of cheap commercial availability of the associated harvesters, which should improve over time as more research effort and resources are devoted to energy harvester development (i.e., small consumer solar cells were much more expensive per watt 10 years ago). Future research could optimize the power efficiency of these energy harvesters, and bulk manufacturing and purchasing could make them lower cost and more accessible. Although we believe many alternative harvesters could be easily integrated into Hapt-Aids, further research would need to be done into the application space of these harvesters and how they could be coupled to useful activities to monitor and generate an appropriate amount of energy. Additionally, although we purposely chose to use haptics as output, we believe that both visual and auditory outputs could easily be integrated into our system, and further research could explore suitable applications for these different output methods.

8.3 Trade-off Between Functionality and Simplicity

The maintenance-free design goal requires Hapt-Aids to be simple, with the trade-off being that users have less flexibility to customize and control the system. A consequence of this is that our devices do not have "off" switches, including when the Hapt-Aid is taken off the body. However, as mentioned, we included a button that allows users to manually discharge the capacitor, essentially acting as a reset button — similar to old-school pedometers.

We make compromises with our Hapt-Aid design based on solutions both more and less complex. Compared to some battery-free wearables, Hapt-Aids still utilize components that are more rigid and add bulk (supercapacitor, potentiometers, etc.). In contrast, some battery-free wearable like chemical indicators (e.g. UV detectors [56]) do not have any circuits and are much more lightweight and flexible. However, Hapt-Aids provide more ease of use through a haptic rather than visual indicator, allowing for more "forgettability" and a more reliable notification. On the other hand, more complex wearables can have integrated MCUs, which allow for more complex vibration patterns. While this could be easily replicated through analog components (i.e., 555 timers), overall our design is intended to create only simple continuous vibrations. We acknowledge that this is a limitation of our current system, but note that complexity is largely useful for immersion, and a single chirp of vibration is typically sufficient for notification delivery.

To compensate for the lack of interface control, we have components that allow manufacturers to modify parameters of the board to tune the Hapt-Aid, introducing a trade-off between system generalizability across users and ease of use. Hapt-Aids can be manufactured with built-in thresholds (e.g., different step amounts) by having the modular factors preset at the factory, i.e., soldering on resistors instead of potentiometers for charge and discharge resistance. That said, this would mean that users would not be able to tune their individual Hapt-Aids. However, if we allow users direct access to modifying the Hapt-Aid, we introduce an extra difficulty in that users would have to test how these changes would reflect in the system. In the future, we could integrate a more intuitive user interface to reduce the mental load on users and make our Hapt-Aids even more adjustable, like having hot-swappable resistors that are rated for specific threshold amounts.

Although our study showed that users generally trusted the device because it performed intuitively as expected, our system currently lacks an interface for device health monitoring. We anticipate that future versions of Hapt-Aid could integrate hardware that would allow for vitality checks of various parts of the system. For example, a pre-charged supercap could be connected to the circuit so that, when a button is pressed, the charge would be released into the board (bypassing the energy harvester) and trigger the haptics, validating that the circuit is intact. However, this would add cost, complexity, and only allow for a number of checks before exhausting the external supercapacitor. With the current form factor, manufacturers could include instructions and accessories to help users verify device functionality. For example, users could be instructed to shine a flashlight on the sun exposure monitor, or manually rotate the bicep rep monitor to observe the device response and confirm that the device is operating properly. Ultimately, the lack of a device health monitoring interface is an inherent limitation of most energy harvesters, and may not be able to be fully overcome with our analog system architecture. However, our low-cost and simple Hapt-Aids are easily and simply replaceable when the user notices that they are not functioning properly anymore.

Finally, another limitation of our system is that there is no logging capability, as Hapt-Aids do not have memory. Our devices are meant for instantaneous notifications, so we cannot retrieve a backlog or history of notifications. Although there are analog ways of implementing memory, they are largely less practical than just having digital components. As a reminder of our system's contribution, Hapt-Aids are not intended to replace existing devices (e.g., smartwatches), which already fulfill users' needs, including logging capabilities. However, we argue that memory-less haptic tags, by providing timely notifications, can significantly impact users' health by delivering sufficient cues to encourage behavior changes for healthier outcomes. In this sense, our system serves as a meaningful complementary technology, offering users of health applications a valuable and effective tool.

9 Conclusion

We present Hapt-Aids: self-powered, on-body haptics for maintenance-free activity monitoring. These small wearables can be deployed on the body and used for a variety of applications. Our system harvests energy directly from activity-specific sources, which it interprets as sensor information and converts to haptic actuation after surpassing a certain threshold. Through this design, Hapt-Aids are extremely cost- and energy-efficient, and retain the "maintenance-free" nature of bandages while gaining sensing and output capabilities. In this work, we present our proof-of-concept modular implementation, and develop and deploy four example end-to-end applications to demonstrate the broad applicability of our system. We believe Hapt-Aids illuminate the potential of a new, lightweight paradigm of passive activity monitoring in health applications.

Acknowledgment

This research was partially supported by the National Science Foundation under the award numbers IIS-2228982.

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A APPENDIX

A.1 Comparisons of Hapt-Aids with Related Work

	Example System	Cost Effectiveness		Power		Complexity		Capability		
		Cost	Reusable /Disposable	Power Source	Power Consumption / Battery Life	Standalone/ Externally Dependent	System Architecture	Functionality	Notification (On the device end)	Feedback Acquisition (On the user end)
Smartwatch	Apple Watch	$249.00	reusable	battery	18 -36 hours	standalone	comphrehensive	wellness monitoring	on-wearable haptic & visual	active & passive
Fitness Trackers	FitBit Inspire 3	$99.95	reusable	battery	36 - 72 hours	standalone	comphrehensive	wellness monitoring	on-wearable haptic & visual	active & passive
	Samsung Gear Fit	$249.98	reusable	battery	72 - 120 hours	standalone	comphrehensive	wellness monitoring	on-wearable haptic & visual	active & passive
	OURA Ring	$349.00	reusable	battery	6 days	externally dependent	battery+sensor+processor +external device (phone)	wellness monitoring	off-wearable haptic & visual	active & passive
	HRM-Pro™ Plus	$129.99	reusable	battery	<12 months	externally dependent	battery+sensor+processor +external device (phone)	heart rate monitor	off-wearable haptic & visual	active & passive
	HEALBE GoBe3	$159.00	reusable	battery	<32 hours	standalone	comphrehensive +external device (phone)	calorie intake, body hydration, neural activity	on-wearable haptic & visual	active & passive
	WHOOP 4.0	$239.00	reusable	battery	5 days	externally dependent	battery+sensor+processor +external device (phone)	wellness monitoring	off-wearable haptic & visual	active & passive
	Polar Verity Sense	$104.95	reusable	battery	18 - 30 hours	externally dependent	battery+sensor+processor +external device (phone)	heart rate monitoring	off-wearable haptic & visual	active & passive
	Nix Hydration Biosensor	$129.00	reusable	battery	36 hours	externally dependent	battery+sensor+processor +external device (phone)	hydration monitoring	off-wearable haptic & visual	active & passive
	Lingo Biosensor	$49.00	reusable	battery	14 days	externally dependent	battery+sensor+processor +external device (phone)	glucose monitoring	off-wearable haptic & visual	active & passive
	STRIV Smart Insole	$339.00	reusable	battery	20 hours	externally dependent	battery+sensor+processor +external device (phone)	workout tracking	off-wearable haptic & visual	active & passive
Pedometers	3DBitBud	$23.99	reusable	battery	12 months	standalone	comphrehensive	step count	on-wearable visual	active
UV Monitor	SunFriend	$49.99	reusable	battery	12 months	standalone	comphrehensive	sun exposure	on-wearable LED	active
	UV Sense	$79.99	reusable	battery	not available	externally dependent	comphrehensive +external device (phone)	sun exposure	off-wearable haptic & visual	active & passive
	sun-a-wear	$89.00	reusable	self-powered	not available	externally dependent	battery+sensor+processor +external device (phone)	sun exposure	off-wearable haptic & visual	active & passive
	SunSense	$95.99-143.99	reusable	battery	3 years	standalone	comphrehensive	sun exposure	on-wearable visual off-wearable haptic	active & passive
UV Patches	SPOTMYUV	$1.03	disposable	passive	-	standalone	non-digital	sun exposure	on-wearable visual	active
	La Roche-Posay's My UV Patch	$30.00	disposable	passive	-	externally dependent	non-digital	sun exposure	off-wearable visual	active
	UV Alert Sunscreen Monitoring Patches	$0.78	disposable	passive	-	standalone	non-digital	sun exposure	on-wearable visual	active
Research Work	RF Bandaid	*$6 est.	reusable	self-powered	35 - 160 μW	externally dependent	harvester+sensors +external RF transceiver	breathing, heart rate, temperature, sound	off-wearable visual	active & passive
Our System	Hapt-Aids	$5-15	reusable	self-powered	0.49 - 45.78 mW	standalone	harvester+actuator	sun exposure, step tracker, bicep rep monitor, location tracker	on-wearable haptic	passive

* Tag only, only counted the cost of key components like BQ25570, LTC6906.
- Comphrehensive system architecture consists of battery, sensors, processors, and actuators like motors and displays.
- Wellness monitoring includes steps, calories, sleep, body temperature heart rate, blood oxygen levels monitoring.
- For wearables connected to smartphones, we consider the notification system to consist of displaying sensor data on the phone screen and sending alerts to users via vibration (i.e., off-wearable visual & haptic). Users can either actively check the phone for feedback, or being notified by the vibration (i.e., active & passive feedback acquisition).

Fig. 15. Supporting table for Figure 4 showing quantitative comparisons of Hapt-Aids and related systems. Example systems include Apple Watch [3], Fitbit [14], Samsung Gear Fit [46], OURA Ring [43], HRM-Pro™ Plus [13], HEALBE GoBe3 [15], Polar Verity Sense [49], WHOOP 4.0 [70], Nix Hydration Biosensor [38], Lingo Biosensor [30], STRIV Smart Insole [57], 3DFitBud [1], UV Sense [50], sun-a-wear [59], SunSense UV Sensor [60], UV Alert Sunscreen Monitor [54], SPOTMYUV [44], RF Bandaid [42]. Additional summaries of wearable UV monitors can also be found in [17].