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Interaction-Power Stations: Turning Environments into Ubiquitous Power Stations for Charging Wearables

Xiaoying Yang
xiaoyingy@ucla.edu
University of California, Los Angeles
Los Angeles, California, USA

Jacob Sayono
jacobsayono@g.ucla.edu
University of California, Los Angeles
Los Angeles, California, USA

Jess Xu
jessicaxu48@g.ucla.edu
University of California, Los Angeles
Los Angeles, California, USA

Yang Zhang
yangzhang@ucla.edu
University of California, Los Angeles
Los Angeles, California, USA

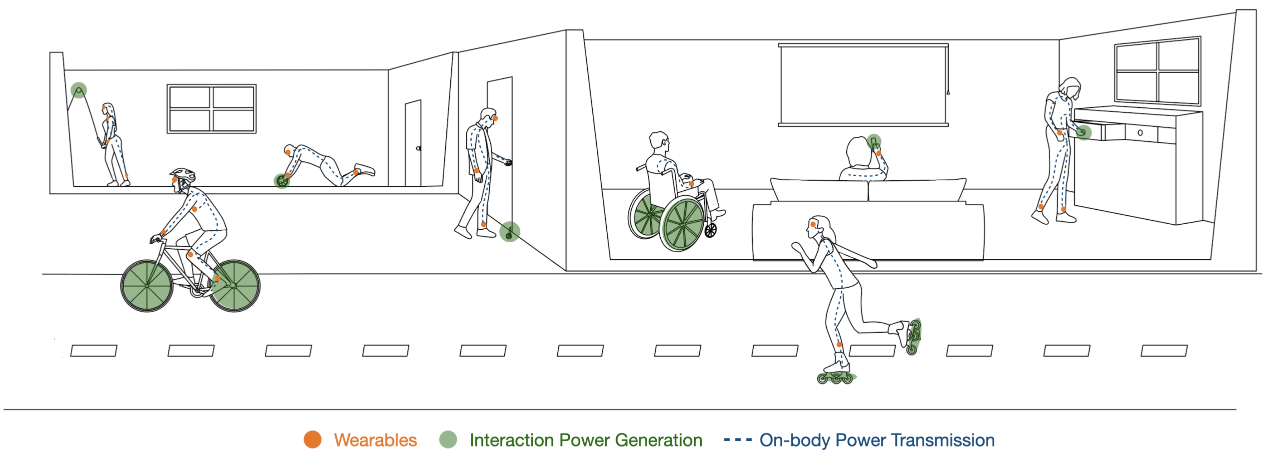

Figure 1: *Interaction-Power Stations* enable power generation and wireless charging to wearables during routine activities, prolonging the lifespan of wearables' batteries and potentially eliminating the necessity to remove them for charging.

ABSTRACT

Despite the promise of wearable devices, people can be discouraged from using them due to the necessity for frequent charging and the subsequent interruption of usage. On another front, an inexhaustible yet unexploited power source can be found in the environment in the form of people's physical interaction with ambient objects, generating a substantial amount of kinetic energy. We proposed *Interaction-Power Stations*, a new energy harvesting approach for wearables, leveraging interaction energy from people and simultaneously charging their wearables through capacitive couplings of the human body. We designed circuits and mechanical mechanisms retrofitted to various objects to convert kinetic energy into electrical signals that travel through the user body at capacitive frequencies, and deliver energy to multiple on-body receivers. We validated our design by preliminary tests and evaluated the system through a short user study which indicates promise for future work.

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CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile computing systems and tools**.

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1 INTRODUCTION

Wearable devices, such as smartwatches, rings, garments, glasses, etc., have been advancing to facilitate ubiquitous sensing of human activities and enrich user interactions with computing resources. However, the adoption of wearable intelligence has been limited due to the need for frequent maintenance of their batteries. Furthermore, the necessity for users to remove these devices for charging purposes interrupts their continuous functionality, leading to a further degradation in user experience, particularly for wearables designed to monitor health and physical activities.

In response to this challenge, researchers have explored novel charging solutions for wearable devices. One solution involves wearables wirelessly drawing power from sources that are either body-worn [37, 38], or on-object [27, 28, 45]. This approach enables the redistribution of power among wearables and eliminates the need for the removal of devices in charging. However, this approach still relies on plugged-in or rechargeable power sources, which poses challenges in terms of scalability and reliability. Another approach seeks energy from the surroundings (e.g., light [20], RF signals [10, 19]) and the human body (e.g., heat [31], sweat [24], breath [11]) to recharge wearables. However, these energy sources considerably vary across space and time, yielding unpredictable harvesting efficiency. On the other hand, integrating generators into wearables, which harness energy from the motions of joints, limbs, and foot strikes, typically yields larger amount of power, in which prior research have shown great promise [2, 7, 40]. Unfortunately, these generators are often perceived as bulky because of the mechanical mechanisms used to harness relative movements between body parts, limiting their practicality, especially in applications requiring continuous daily uses.

The aforementioned challenges prompted us to investigate an alternative wearable charging approach that is capable of (1) collecting sufficient energy with an unobtrusive wearable form factor, (2) providing ubiquitous, versatile, and scalable charging to wearables, while (3) ensuring sustainability and usability. We notice that user interactions with everyday objects (e.g., opening/closing doors, working out with exercise tools), which contain significant amounts of kinetic energy, serve as exploitable power sources in user environments, as demonstrated in prior work [17, 34, 46]. Furthermore, we found that these interactions often involve users' physical contact with objects, making the human body a convenient transmission medium for energy flow between the environment and wearable devices.

In this paper, we propose *Interaction-Power Stations*, an power generation system that harvests user interaction power to charge wearables. Power is generated when users interact with instrumented objects during daily activities, then it is converted into high-frequency signals that propagate through a user's body to wearables via capacitive coupling. Our work introduces a novel implementation of energy harvesting for wearables while not requiring harvesters to be featured on wearables, enabling a lightweight form factor. In fact, this power delivery scheme has long been embraced by industrial power stations, where electrical power is produced on a concentrated and significant scale and then transmitted through power lines to appliances in residential areas. Similarly, our research turns the environment into ubiquitous power stations and leverages the human body as the "power lines" for power delivery, establishing an intuitive link between harvesters and wearables. The closest prior work to this research is ShaZam [27], which investigated power transfer from objects to wearables using a powered signal generator. However, incorporating interaction-powered transmitters into everyday objects introduces new design and technical challenges that remain largely unexplored. This underscores the significance of our work.

We developed an end-to-end power generation and transmission system with customized hardware to prove the feasibility of our approach, consisting of (1) motor and gear mechanisms retrofitted to existing objects to harvest interaction energy, (2) transmitters that deliver harvested energy to wearables, and (3) receivers that collect energy from human body. We evaluated our system through preliminary validation tests and a short user study including three wearable locations with three tested objects. Our results showed average amounts of harvested energy of 66.3 μJ, 0.87 μJ and 0.08 μJ from one revolution of biking, one trial of door opening/closing, and one revolution of cranking respectively, when receivers' grounding conditions were improved by connections with floating measuring probes. Given the frequent manipulation of everyday objects, we anticipate that the seemingly minimal energy identified in our study will accumulate to a significant volume to serve as a practical, supplementary power source for wearables. These preliminary research findings point at promising directions for future improvements on interaction-powered wearable charging systems to eliminate constraints imposed by grounding conditions, and are expected to have higher efficiency, enabling a new charging scheme to strengthen wearable devices' benefits.

2 RELATED WORK

2.1 Human as Power Source

Human body is a rich source of energy for interactive devices, including thermal energy [31], chemical energy [24] and kinetic energy [17, 34, 40]. The combination of multiple energy sources has been leveraged in clothing and wearables to maximize energy utilization and enhance overall efficiency [11]. Closer to our research is prior work that investigated user interaction-excited power generation. Traditional interaction energy harvesting relies on power generation from intentional user actions such as cranking, shaking, and twisting [4, 21, 35, 43]. For example, users can turn cranks to power flashlights whenever light is needed, but the cranking motions are considered *extrinsic* to users' interaction with flashlights – cranking is an additional movement a user has to perform before flipping the toggle flashlight button, which on the other hand is intrinsic. Recent research has been shifting towards implicit interaction energy harvesting, where power generation is *intrinsic* to original interactions of objects [12, 15, 46]. *Interaction-Power Stations* builds upon the growing interest in this area, and expands the use of interaction power to charging wearable devices.

2.2 Human as Power Transmission Medium

Human body has been modeled as conductive line, resistor, capacitor, antenna, and ground in various applications [16]. Electricity has been employed on the human body to alter haptic sensations for interactivity enhancement [29] and tactile texture rendering [5]. Electrical muscle stimulation (EMS) technology has been used to assist learning of musical instruments [30], and provide body movement actuation [39]. Prior work has also applied signals to human bodies for sensing purposes, including user recognition [36], on-skin touch sensing [47, 48], activity recognition [18], and communication [41]. Closer to our research is prior work that leverages human body as a medium to transmit power. For example, SkinnyPower [37] enables power transfer from battery-powered wearables to other battery-free on-body devices, while ShaZam [27] and CASPER [45] focused on obtaining power from objects that have active power sources and are in contact with the user body. These works utilize capacitive coupling, a technique also leveraged by our research. Nevertheless, our work sets itself apart from prior

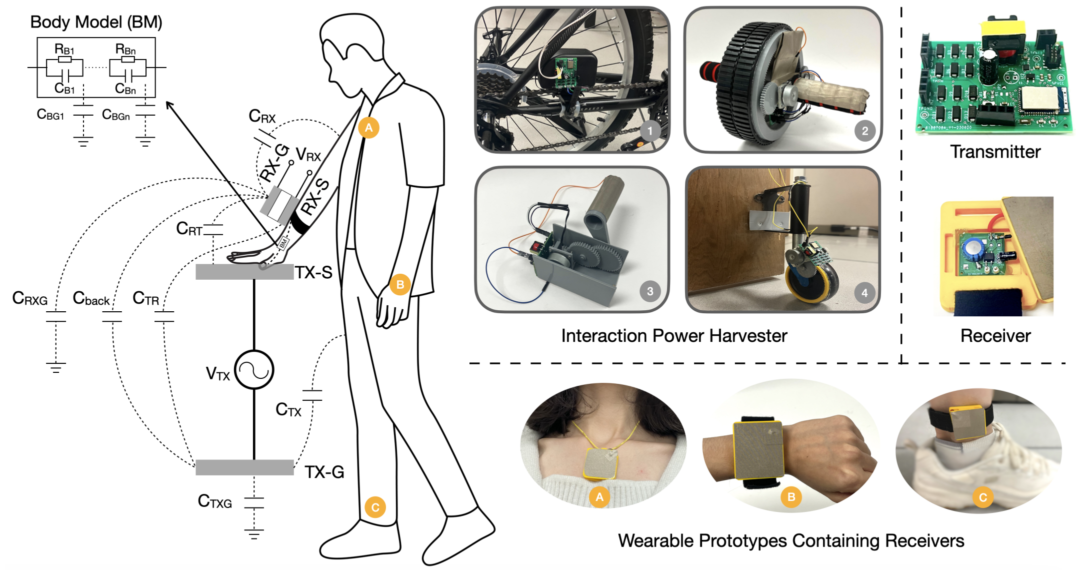

Figure 2: Left: Illustration of capacitive coupling via human body, transmitters, receivers, and the ground. Right from top to bottom: Interaction power harvesters on (1) bicycle (2) roller wheel (3) hand crank (4) door; Hardware of transmitter and receiver; Three wearable prototypes containing receivers: (A) necklace (B) smartwatch (C) anklet. Note that throughout the paper we refer to our prototypes using names of commonly seen wearables (e.g., smartwatches) to differentiate their locations.

works by using power generated from user interactions, facilitating a flexible and sustainable power supply for wearable devices.

3 PRINCIPLES OF OPERATION

The conductivity of human body allows it to form a capacitive link with external conductive elements that carry signals in the Electro-Quasistatic (EQS) range (typically less than 1 MHz), where electric field dominates and the signals primarily flow through the human body. A demonstrative model is shown in Figure 2 left. A transmitter signal electrode (TX-S) and a receiver electrode (RX-S) are in contact with the human body, forming an through-body power flow (forward path). A transmitter grounding electrode (TX-G) and a receiver grounding electrode (RX-G) are floating over the air, coupling with the human body and the earth ground through the air to form a return path. An electrical potential (V_{RX}) is generated between RX-S and RX-G, realizing the power transfer from the transmitter to the receiver [8].

Prior work has investigated a simplified equivalent circuit model of human body-involved capacitive coupling, as shown in Figure 3 [8, 13, 22, 26]. In this model, C_B and R_B denote human body capacitance and resistance, while C_{BG} denotes the capacitance between human body and ground. This model assumes (1) human body shows equal potential throughout human body in EQS frequency region, and can be approximated as a single point node (2) dimmed components (C_{TR}, C_{RT}) have negligible effect and thus excluded from the equivalent model (3) C_{back} is merged to C_{TXG} and C_{RXG} [22, 26].

There are generally two approaches to increase the power delivered to the load on the receiver: (1) with a certain hardware and body setup (C_{TXG}, C_{RXG}, C_{BG} and C_{RX}), increasing V_{TX} could increase V_{RX}, and (2) with a certain V_{TX}, impedance matching on the transmitter or receiver side could maximize power transfer from V_{TX} to V_{RX}, and V_{RX} to V_L respectively. Due to the capacitive nature of the load impedance looking from the transmitter outward, inserting an inductor L_{TX} can compensate the impedance of the return path and increase the voltage gain with a series of approximations [26]. Similarly, an inductor L_{RX} on the receiver end can further increase V_L. In addition, a high impedance load termination is expected to avoid most voltage drop across the human body [22]. Heuristically, these criteria guided the design and validation of our system, which will be detailed in later sections.

To generate stable high-frequency signals for capacitive coupling, we adopted a common approach with the rectifier-inverter-transformer converting topology (Figure 3). With this topology, the inverter convert DC power into AC power featuring a controllable frequency. The use of transformers can (1) boost up the output voltage of the inverter (i.e., increase V_{TX}) and (2) introduce inductance to cancel the return path capacitance, increasing the voltage of the receiver V_{RX}. For these merits, our system utilized this topology to transform harvested power into energy carrier signals to transmit through the human body. Details of our system implementation can be found in Section 4.

4 IMPLEMENTATION

Our system consists of three main components: (1) mechanisms instrumented to objects that convert kinetic energy into electrical energy during interactions, (2) a power transmitter that delivers power to the human body, and (3) a power receiver that obtains power from the human body. We proceeded to conduct a validation process on each component, which proved their effectiveness and

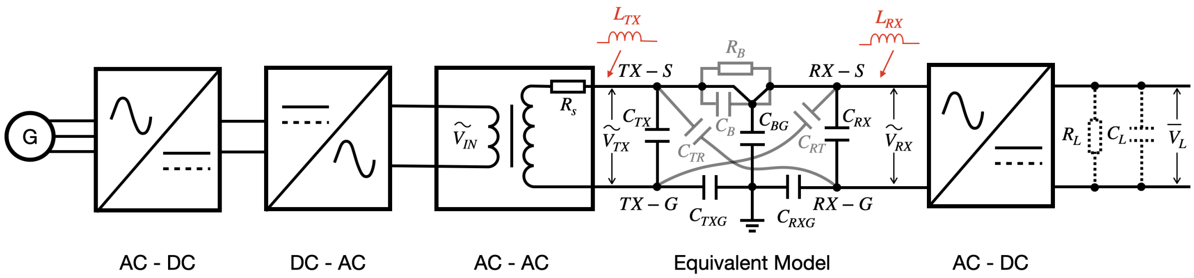

Figure 3: Electrical path and equivalent model of human body-involved capacitive coupling in our system. Dimmed components have negligible effect and thus excluded from the equivalent model. "G" denotes the generator.

comprehended the factors affecting their charging efficiency. To demonstrate *Interaction-Power Stations*, we integrated our system components with accompanying 3D printed interaction harvesters into four representative objects – a door, a bicycle, a roller wheel, and a 3D printed hand cranker.

4.1 Interaction Power Harvester

Users interactions with objects (e.g., pulling, twisting) consist of various types of motions of limbs, which can be converted into rotational motions using gear mechanisms to facilitate the use of motor generators for harvesting kinetic energy as a common practice [40, 46]. These harvesters should: (1) harvest as much energy as possible, (2) minimize the impact on the usability of their host objects, and (3) be non-intrusive to the environment. Adding gearboxes can increase the ratio between the rotational speed of the generator shaft and the input interaction leading to increased power generation, which is, however, at the cost of requiring users to apply greater forces for manipulation that could lower usability. We used the chain fixtures of an off-the-shelf device for bicycle [23], and customized mechanisms with different gear ratios and number of generators for other objects, considering the space and length of interaction strokes of each object, and the minimum and maximum power limits of the power transmitter (Figure 2). The harvesters were made by 3D printing and integrated with three-phase AC motors [9] to generate electrical power from mechanical movements.

4.2 Power Transmitter

Figure 2 shows our transmitter. The output of the motor is low-frequency AC signals, which is not ideal for inducing capacitive couplings through the user body. To increase and control their frequencies, we used an AC-DC-AC conversion topology as discussed in Section 3. The AC output of the motor is followed by a rectifier (CDBHD140L) and a low-dropout voltage regulator (MCP1703) to generate a 3.3V voltage for an ultra-low-power controller module (MDBT42Q-512KV2), which can generate up to 4 MHz control signals with a 16 MHz system clock to the inverter. The rectified DC motor output is turned into high-frequency (i.e., 250 kHz) AC signals using an H-bridge inverter (DRV8837), and then amplified by a transformer that improves power delivered to the load while lowering the transmitted current for skin safety. The AC signals are applied to a pair of electrodes, one floating in the air serving as the ground electrode (TX-G), and the other (TX-S) positioned in the area where users come into contact with their bodies during interactions (i.e., handles, crank). Two types of materials were employed for electrodes to facilitate applications with various sizes, shapes and comfort during contact: Faraday fabric [3] and conductive fabric [1].

4.3 Power Receiver

We made multiple wearable prototypes (Figure 2), each of which features a 3D-printed casing, with a signal electrode (RX-S) on the underside in contact with the skin and a grounding electrode (RX-G) on top coupling through the air. Our receiver electrodes feature the same fabrics as the ones used on the transmitter. The dimensions are 46×37×12 (mm) for smartwatch, and 30×28×9 (mm) for anklet and necklace, considering the form factor of commercial smartwatch and wearables. The power fed to the receiver is rectified by a full-wave rectifier (CDBHD140L) with low forward-voltage and consistent performance, and then stored to a 0.01 F super capacitor (KEMET FYL0H103ZF). This capacitor is probed with a unplugged multimeter in our later tests. In real-world applications, energy stored in this capacitor can be siphoned, boosted and transferred to a wearable battery, the process of which is standard and efficient (e.g., > 90% for BQ25504 [14]), and thus is not evaluated in our work.

4.4 Technical Validation

4.4.1 Transmitter Validation. The manipulation of objects by users leads to varying rotational speeds of generators, consequently resulting in distinct transmitter outputs. We first ran a test to validate our transmitter's capability of outputting effective excitation signals under different speeds. Specifically, we used a coaxial powered motor to drive the power generator, which is connected to the transmitter board we designed. The transmitter was configured to output a 250 kHz AC signal. An experimenter wore the smartwatch and positioned the hand on a transmitter signal electrode of 10×20 (cm), similar to the size of a palm. The ground electrode is placed 30 cm apart at a size of 20×20 (cm). The dimensions and positions of these electrodes are on average similar to those used in real-world mechanisms. We adjusted the spinning speed of the motor and measured the corresponding generator output (i.e., V_G) and transmitter output (i.e., V_{TX}), both of which are AC signals and are evaluated by their peak-to-peak values and frequency. The result is shown in Figure 4 top. As V_G increases (i.e., rotating speed increases), V_{TX}

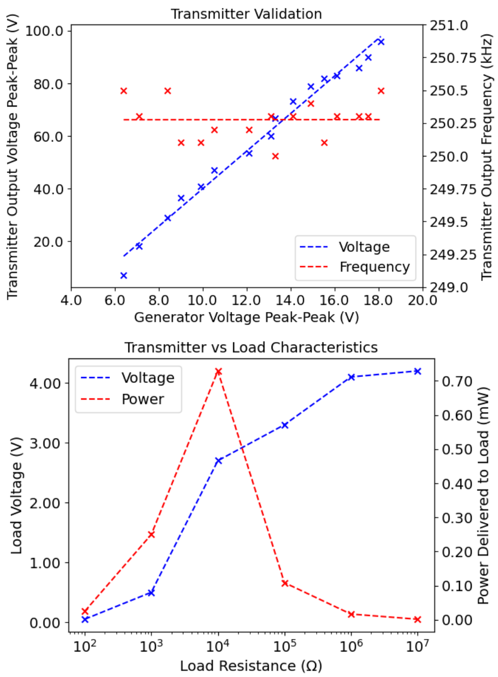

Figure 4: Transmitter validation. Top: variation of peak-to-peak voltage and frequency of transmitter output with output voltage of the generator. Bottom: variation of power delivered to different resistive loads.

increases proportionally, indicating a greater amount of power output given the same load. The stability of V_{TX} at 250 kHz proved the transmitter's efficacy in converting signals with varying magnitudes and voltages into AC signals with consistent frequency for capacitive coupling excitation. In addition, we measured a maximum of 4 mA of current and 5 V voltage across human body (i.e., TX-S and RX-S), well below the safety threshold of power (Section 6.1) and imperceptible to users.

4.4.2 Receiver Validation. The load characteristic has an impact on the amount and the efficiency of power absorbed by the receiver, due to capacitive-dominated high impedance of power sources. To validate this effect, we set up the load with various resistance and capacitance configurations, and measured the power delivered to the load. We used the same setup as described in Section 4.4.1, and configured the transmitter to produce around 45 V peak-to-peak, simulating the average rotating speed of generators during interactions. Figure 4 bottom shows the power delivery with resistive loads (100 Ω - 10 MΩ). The power reaches at its maximum (more than 0.6 mW) when R_L is at a few kilo-ohms, implying an estimated internal source resistance of a similar magnitude. This is consistent with our previous discussion. Additionally, we investigated the power performance of the receiver with a capacitive load as an energy storage element, including a 470 uF tantalum capacitor (0.4Ω ESR) and a 0.01 F super capacitor (< 300Ω ESR), which showed a maximum charging rate of 0.18 mW and 0.05 mW respectively. Due to capacitive loads yielding lower harvested energy, we chose to use them to determine the lower bounds of battery charging efficiency in subsequent evaluations.

5 EVALUATION

To evaluate the power transmission performance of our approach, we conducted studies on three mechanisms (door, bicycle, and crank) with five participants (2 females, mean age=26). Before the study, we informed the participants that our system met safety requirements (Section 6.1). During the study, each participant was instructed to operate each mechanism for three rounds with three wearables on their body: a necklace, a smartwatch, and an anklet (Figure 2 A-C). For the door, each round consisted of two trials (i.e., one trial consists of one opening and one closing operation). For the bicycle and crank, each round consisted of participants actively engaging with the mechanisms for ten cycles. After one round of tests, we took measurements on the voltage of the receiver capacitor and calculated the energy using $CU^2/2$, after which we released the power of the capacitor and started the next round of tests.

On average, the energy delivered to the smartwatch, anklet and necklace was 0.29 μJ (SD=0.28), 0.37 μJ (SD=0.14), 0.21 μJ (SD=0.27) for each trial of interacting with the door. The number is 13.3 uJ (SD=5.6), 50.5 μJ (SD=25.2), 2.5 μJ (SD=1.5) for one cycle of operation of the bicycle, and 0.06 μJ (SD=0.03), 0.006 μJ (SD=0.004) and 0.01 μJ (SD=0.01) for one cycle of the crank. Figure 5 shows the results split into individuals, from which we observed a significant difference in the power allocation across various receivers in the body. Cranking delivered more power to the smartwatch than others, while anklet has the greatest ability of drawing power when bicycling, primarily due to the different coupling characteristics resulting from the electrode size and positions relative to receivers. Our door setup received the largest variation across receiver location and participant among all setups, for both electrodes and participants being in motion during the opening/closing operations, which made the coupling paths less consistent.

Though the energy delivered to receiver per interaction is at μJ level with our current implementation, this energy can accumulate quickly as people frequently interact with their physical environments, and can spend a long time (easily consisting of thousands and more cycles) on mobility and exercise tools. For example, a 30-minute bicycling is estimated to supply the power of Fitness Tracker [44] app on a smart wristband for more than one hour, while charging other wearables the wristband user is wearing simultaneously. Advancements in ultra-low power electronics for wearables, including Bluetooth Low Energy (BLE) [32], LCDs [25], and accelerometers [6], have led to μW-level power consumption, paving the way for the future adoption of through-body power transfer as a source of energy for wearables. Our evaluation also reveals constraints from grounding conditions as the disconnection with multimeter probes (i.e., roughly 1m length, unplugged from common ground) reduced harvested energy amount by a significant 95%. Though the multimeter was not grounded, our electrode design should be improved in the future to improve grounding conditions to eliminate the need for floating electrodes. Nevertheless, our research shows promise as a supplementary power supply for wearables, with room for further improvement on its power delivery efficiency.

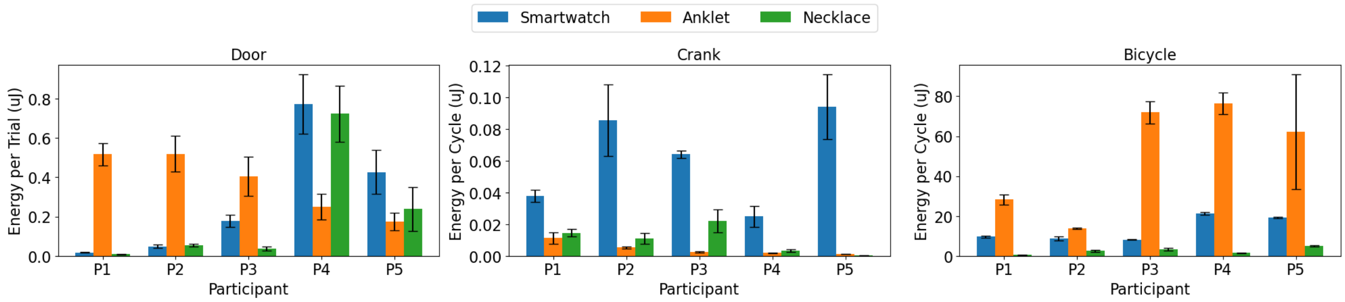

Figure 5: Energy received by different wearables grouped by instrumented object.

6 DISCUSSION

6.1 Safety Regulations

Prior work has outlined the safety regulations for applying electricity on the human body [16, 27, 45] under international guidelines [33]. The major regulations considered in our research include a maximum contact current of 20 mA and a maximum whole-body Specific Energy Absorption Rate (SAR) of 0.08 W/kg at a frequency of 100 kHz-110 MHz.

Our system adheres to these regulations throughout the design, testing, and research process, with specific measurements presented in Section 4.4 verifying the safety of our system. In addition, power only exists at the power transmitter when people actively interact with objects in our approach, further mitigating the potential risks of long-term constant exposure to electricity. However, we are cautious about drawing any conclusions on health implications and expect future in-depth investigations to shed more light.

6.2 Comparison with Prior Work

Power transfer efficiency is specific to transceiver and electrode design and their placements, load characteristics, and the surrounding environment, making it hard to establish criteria to assess the system performance. Prior work has realized through-body power transfer at a charging rate of 1 mW for wearable-to-wearable scenario [37], 0.1-0.9 mW [45], 0.5-1 mW [27], 0.005-0.25 mW [26], 1.385 mW [8] for object-to-wearable scenario, all of which utilized active power sources on the transmitter side that served as an inexhaustible power tanks to deliver power to receivers. In comparison, our approach achieved a charging rate of 0.05-0.6 mW with customized power generating mechanisms as the front end of the transmitter, which consumes non-negligible energy to convert interaction power, bounded by a user's motor characteristics into effective excitation signals for through-body power transmission. While there is room for future enhancements in power management, *Interaction-Power Stations* has achieved comparable performance with previous efforts, showing promise of through-body power transfer sourcing energy from user interactions.

6.3 Supplemental Use Scenarios

Interaction-Power Stations could associate human activities with the customizable characteristics (e.g., frequency) of the AC output from the transmitter. As shown in Section 4.4, the frequency of the transmitter output is largely consistent as the speed of the generator changes (i.e., throughout the interaction process at different speeds), making it an ideal ID carrier for different objects and the activities they are engaged in. Specifically, this could be implemented by configuring the switching frequency of the inverter.

The employment of our system for activity recognition is complimentary to existing body of research which identifies Electromagnetic signals emitted from electrical appliances during their operations [18]. Our system extends this sensing principle to include passive objects (i.e., those that do not operate on electricity), making them compatible with it. Future work is needed to balance between power delivery and information conveyance efficiency.

6.4 Human-Oriented Factors on Power Transfer

Drawing from the modeling in Section 3, power transfer performance is sensitive to model parameters to which human body-oriented factors contribute. Key factors include human posture, which has been empirically shown that can affect capacitance and power transfer efficiency due to the change of relative distances between human body, transmitter and receiver electrodes [42]. Another significant factor is the force/torque applied by the user to the generator. Empirically, although force/torque determines the input power, we did not observe its influence on the power delivery efficiency, which is the ratio of output power to input power. Future research will delve deeper into how these human factors could influence the power delivery efficiency. Additionally, the impact of factors such as bio-metric data (i.e., height, weight, skin moisture), clothing, and body hair should also be investigated.

7 CONCLUSION

We present *Interaction-Power Stations*, an interaction power harvesting and transmitting system to charge wearables using human body as a transmission medium. We designed energy harvesting gear mechanisms for various objects, demonstrating the pervasive presence of interaction power throughout the environment. We also developed a custom circuit that features conversion between AC and DC signals, frequency adjustment, and power amplification. With validation tests and a user study, our approach has shown great potential in turning objects into ubiquitous power stations, introducing a new energy delivery scheme for wearables, and making both interaction power as well as wearables more useful.

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REFERENCES

[1] Adafruit. 2023. Nylon Conductive Fabric. https://www.adafruit.com/product/4762 Last accessed 14 Sep 2023.

[2] Ahsan Ali, Hamna Shaukat, Saira Bibi, Wael A Altabey, Mohammad Noori, and Sallam A Kouritem. 2023. Recent progress in Energy Harvesting Systems for wearable technology. *Energy Strategy Reviews* 49 (2023), 101124.

[3] ATMOSURE. 2023. Faraday Fabric. https://a.co/d/2VGZnau Last accessed 14 Sep 2023.

[4] Akash Badshah, Sidhant Gupta, Gabe Cohn, Nicolas Villar, Steve Hodges, and Shwetak N. Patel. 2011. Interactive Generator: A Self-Powered Haptic Feedback Device. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2051–2054. https://doi.org/10.1145/1978942.1979240

[5] Olivier Bau and Ivan Poupyrev. 2012. REVEL: Tactile Feedback Technology for Augmented Reality. *ACM Trans. Graph.* 31, 4, Article 89 (jul 2012), 11 pages. https://doi.org/10.1145/2185520.2185585

[6] BOSCH. 2023. Acceleration sensor. https://www.bosch-sensortec.com/products/motion-sensors/accelerometers/bma400/ Last accessed 14 Sep 2023.

[7] Mingjing Cai, Zhaoshu Yang, Junyi Cao, and Wei-Hsin Liao. 2020. Recent advances in human motion excited energy harvesting systems for wearables. *Energy Technology* 8, 10 (2020), 2000533.

[8] Hyungjoo Cho, Ji-Hoon Suh, Chul Kim, Sohmyung Ha, and Minkyu Je. 2022. An Intra-Body Power Transfer System With $>$1-mW Power Delivered to the Load and 3.3-V DC Output at 160-cm of on-Body Distance. *IEEE Transactions on Biomedical Circuits and Systems* 16, 5 (2022), 852–866.

[9] CrocSee. 2023. Micro 3 Phase AC Mini Hand Brushless Motor. https://a.co/d/gW2PfyH Last accessed 14 Sep 2023.

[10] Minhao Cui, Qing Wang, and Jie Xiong. 2023. Bracelet+: Harvesting the Leaked RF Energy in VLC with Wearable Bracelet Antenna. In *Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems* (Boston, Massachusetts) *(SenSys '22)*. Association for Computing Machinery, New York, NY, USA, 250–262. https://doi.org/10.1145/3560905.3568526

[11] Alexander Curtiss, Blaine Rothrock, Abu Bakar, Nivedita Arora, Jason Huang, Zachary Englhardt, Aaron-Patrick Empedrado, Chixiang Wang, Saad Ahmed, Yang Zhang, Nabil Alshurafa, and Josiah Hester. 2022. FaceBit: Smart Face Masks Platform. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5, 4, Article 151 (dec 2022), 44 pages. https://doi.org/10.1145/3494991

[12] Jasper de Winkel, Vito Kortbeek, Josiah Hester, and Przemysław Pawełczak. 2020. Battery-Free Game Boy. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 3, Article 111 (sep 2020), 34 pages. https://doi.org/10.1145/3411839

[13] Tobias Grosse-Puppendahl, Christian Holz, Gabe Cohn, Raphael Wimmer, Oskar Bechtold, Steve Hodges, Matthew S Reynolds, and Joshua R Smith. 2017. Finding common ground: A survey of capacitive sensing in human-computer interaction. In *Proceedings of the 2017 CHI conference on human factors in computing systems.* 3293–3315.

[14] Texas Instruments. 2023. Ultra Low Power Boost Converter with Battery Management for Energy Harvester | Nano-Power Management. https://www.ti.com/product/BQ25504 Last accessed 14 Sep 2023.

[15] Mustafa Emre Karagozler, Ivan Poupyrev, Gary K Fedder, and Yuri Suzuki. 2013. Paper generators: harvesting energy from touching, rubbing and sliding. In *Proceedings of the 26th annual ACM symposium on User interface software and technology.* 23–30.

[16] Michinari Kono, Takumi Takahashi, Hiromi Nakamura, Takashi Miyaki, and Jun Rekimoto. 2018. Design guideline for developing safe systems that apply electricity to the human body. *ACM Transactions on Computer-Human Interaction (TOCHI)* 25, 3 (2018), 1–36.

[17] Robert Kovacs, Lukas Rambold, Lukas Fritzsche, Dominik Meier, Jotaro Shigeyama, Shohei Katakura, Ran Zhang, and Patrick Baudisch. 2021. Trusscillator: A System for Fabricating Human-Scale Human-Powered Oscillating Devices. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1074–1088. https://doi.org/10.1145/3472749.3474807

[18] Gierad Laput, Chouchang Yang, Robert Xiao, Alanson Sample, and Chris Harrison. 2015. Em-sense: Touch recognition of uninstrumented, electrical and electromechanical objects. In *Proceedings of the 28th annual ACM symposium on user interface software & technology.* 157–166.

[19] Jiamin Li, Yilong Dong, Jeong Hoan Park, and Jerald Yoo. 2021. Body-coupled power transmission and energy harvesting. *Nature Electronics* 4, 7 (2021), 530–538.

[20] Yichen Li, Tianxing Li, Ruchir A. Patel, Xing-Dong Yang, and Xia Zhou. 2018. Self-Powered Gesture Recognition with Ambient Light. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 595–608. https://doi.org/10.1145/3242587.3242635

[21] Anders Lundström and Ylva Fernaeus. 2022. Making Crank-Powered Interactions: Methods, Demonstrators, Materials. In *Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 913–924. https://doi.org/10.1145/3532106.3533453

[22] Shovan Maity, Mingxuan He, Mayukh Nath, Debayan Das, Baibhab Chatterjee, and Shreyas Sen. 2018. Bio-physical modeling, characterization, and optimization of electro-quasistatic human body communication. *IEEE Transactions on Biomedical Engineering* 66, 6 (2018), 1791–1802.

[23] Mankukulam. 2023. Bike Electric Generator. https://a.co/d/4yddYHV Last accessed 14 Sep 2023.

[24] Patrick Mercier and Joseph Wang. 2020. Powered by sweat: Throw out the batteries: Biofuels will change the future of wearable devices. *IEEE Spectrum* 57, 7 (2020), 28–33.

[25] Sharp Microelectronics. 2023. Graphic LCD Display Module Transflective TFT. https://sharpsecd.com/static/media/LS027B7DH01%20Spec%20(LD-28305A).02b53ab6.pdf Last accessed 14 Sep 2023.

[26] Nirmoy Modak, Debayan Das, Mayukh Nath, Baibhab Chatterjee, Gaurav Kumar, Shovan Maity, and Shreyas Sen. 2022. EQS Res-HBC: A 65-nm electro-quasistatic resonant 5–240 μW human whole-body powering and 2.19 μW communication SoC with automatic maximum resonant power tracking. *IEEE Journal of Solid-State Circuits* 57, 3 (2022), 831–844.

[27] Noor Mohammed, Rui Wang, Robert W Jackson, Yeonsik Noh, Jeremy Gummeson, and Sunghoon Ivan Lee. 2021. ShaZam: Charge-free wearable devices via intra-body power transfer from everyday objects. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5, 2 (2021), 1–25.

[28] Rafael Morales González, Asier Marzo, Euan Freeman, William Frier, and Orestis Georgiou. 2021. Ultrapower: Powering tangible & wearable devices with focused ultrasound. In *proceedings of the fifteenth international conference on tangible, embedded, and embodied interaction.* 1–13.

[29] Adiyan Mujibiya. 2015. Corona: Interactivity of body electrostatics in mobile scenarios using wearable high-voltage static charger. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services.* 435–444.

[30] Romain Nith, Shan-Yuan Teng, Pengyu Li, Yujie Tao, and Pedro Lopes. 2021. DextrEMS: Increasing Dexterity in Electrical Muscle Stimulation by Combining It with Brakes. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 414–430. https://doi.org/10.1145/3472749.3474759

[31] Amin Nozariasbmarz, Henry Collins, Kelvin Dsouza, Mobarak Hossain Polash, Mahshid Hosseini, Melissa Hyland, Jie Liu, Abhishek Malhotra, Francisco Matos Ortiz, Farzad Mohaddes, et al. 2020. Review of wearable thermoelectric energy harvesting: From body temperature to electronic systems. *Applied Energy* 258 (2020), 114069.

[32] NXP. 2023. Ultra-Low-Power Bluetooth Low Energy System on Chip Solution. https://www.nxp.com/docs/en/nxp/data-sheets/QN908x.pdf Last accessed 14 Sep 2023.

[33] International Commission on Non-Ionizing Radiation Protection et al. 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health physics* 74, 4 (1998), 494–522.

[34] James Pierce and Eric Paulos. 2012. Designing everyday technologies with human-power and interactive microgeneration. In *Proceedings of the Designing Interactive Systems Conference.* 602–611.

[35] Kimiko Ryokai, Peiqi Su, Eungchan Kim, and Bob Rollins. 2014. EnergyBugs: Energy Harvesting Wearables for Children. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 1039–1048. https://doi.org/10.1145/2556288.2557225

[36] Munehiko Sato, Rohan S Puri, Alex Olwal, Yosuke Ushigome, Lukas Franciszkiewicz, Deepak Chandra, Ivan Poupyrev, and Ramesh Raskar. 2017. Zensei: Embedded, multi-electrode bioimpedance sensing for implicit, ubiquitous user recognition. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* 3972–3985.

[37] Rishi Shukla, Neev Kiran, Rui Wang, Jeremy Gummeson, and Sunghoon Ivan Lee. 2019. SkinnyPower: enabling batteryless wearable sensors via intra-body power transfer. In *Proceedings of the 17th Conference on Embedded Networked Sensor Systems.* 68–82.

[38] Ryo Takahashi, Wakako Yukita, Tomoyuki Yokota, Takao Someya, and Yoshihiro Kawahara. 2022. Meander Coil++: A body-scale wireless power transmission using safe-to-body and energy-efficient transmitter coil. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems.* 1–12.

[39] Yudai Tanaka, Jun Nishida, and Pedro Lopes. 2022. Electrical Head Actuation: Enabling Interactive Systems to Directly Manipulate Head Orientation. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (<conf-loc>, <city>New Orleans</city>, <state>LA</state>, <country>USA</country>, </conf-loc>) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 262, 15 pages. https://doi.org/10.1145/3491102.3501910

[40] Shan-Yuan Teng, K. D. Wu, Jacqueline Chen, and Pedro Lopes. 2022. Prolonging VR Haptic Experiences by Harvesting Kinetic Energy from the User. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 39, 18 pages. https://doi.org/10.1145/3526113.3545635

[41] Virag Varga, Gergely Vakulya, Alanson Sample, and Thomas R Gross. 2018. Enabling interactive infrastructure with body channel communication. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 4 (2018), 1–29.

[42] Virag Varga, Marc Wyss, Gergely Vakulya, Alanson Sample, and Thomas R. Gross. 2018. Designing Groundless Body Channel Communication Systems: Performance and Implications. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 683–695. https://doi.org/10.1145/3242587.3242622

[43] Nicolas Villar and Steve Hodges. 2010. The Peppermill: A Human-Powered User Interface Device. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 29–32. https://doi.org/10.1145/1709886.1709927

[44] Vivofit. 2023. Fitness Tracker. https://www.garmin.com/en-US/p/582444 Last accessed 14 Sep 2023.

[45] Edward J Wang, Manuja Sharma, Yiran Zhao, and Shwetak N Patel. 2018. CASPER: Capacitive serendipitous power transfer for through-body charging of multiple wearable devices. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. 188–195.

[46] Xiaoying Yang, Jacob Sayono, Jess Xu, Jiahao Nick Li, Josiah Hester, and Yang Zhang. 2022. MiniKers: Interaction-Powered Smart Environment Automation. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 3, Article 149 (sep 2022), 22 pages. https://doi.org/10.1145/3550287

[47] Yang Zhang, Wolf Kienzle, Yanjun Ma, Shiu S Ng, Hrvoje Benko, and Chris Harrison. 2019. ActiTouch: Robust touch detection for on-skin AR/VR interfaces. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 1151–1159.

[48] Yang Zhang, Junhan Zhou, Gierad Laput, and Chris Harrison. 2016. Skintrack: Using the body as an electrical waveguide for continuous finger tracking on the skin. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 1491–1503.