

RESEARCH ARTICLE

Full-Textile Electrostimulation Realizing Electrical Waste Reduction

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ABSTRACT

Wearable electrostimulation devices can enhance exercise performance and aid recovery; however, traditional systems often require external power sources and wiring, which limit mobility and contribute to electronic waste (e-waste). In this study, we introduce WE-Stim, a fully textile-based electrostimulation system that integrates stimulation directly into clothing, eliminating the need for additional devices. Using body-coupled energy transfer (BcET) and a unique arrangement of conductive and insulating materials, WE-Stim delivers on-demand electrical stimulation without batteries or generators. The system is designed through finite element analysis (FEA) and validated with human physiological performance tests and wearability studies. Results demonstrated substantial improvements in exercise performance, along with reductions in muscle soreness and edema. WE-Stim presents a practical, sustainable solution for wearable electrostimulation, addressing the limitations of traditional systems by providing wireless, efficient stimulation for daily use.

1 | Introduction

Electrostimulation (ES) devices have demonstrated significant promise, with numerous FDA-approved products showing efficacy across various applications, including neurological disorders [1–3], musculoskeletal systems [4, 5], and tissue regeneration [6–8]. Increasing accessibility and user-friendliness have become a priority, leading to the development of wearable platforms that enable seamless electrical stimulation during daily activities and sports [9–17]. The global market for wearable devices is projected to reach \$57.6 billion by 2022, with annual ship-

ments expected to exceed 200 million units, underscoring their substantial impact in health and fitness [18, 19]. Despite the rapid growth of wearable technology, sustainability concerns, especially regarding electronic waste (e-waste), are rising [20]. E-waste is the fastest-growing waste stream globally, projected to reach 74 million metric tons by 2030, up from 59.4 million in 2022 [21, 22]. Most wearables depend on non-renewable resources, such as lithium and cobalt, for batteries, which not only deplete critical materials but also contribute to environmental pollution through lead and mercury release upon disposal [23]. ES devices, in particular, often require additional power sources and

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wiring, complicating integration into wearables and exacerbating the e-waste issue. While recent efforts have aimed at developing eco-friendly materials and reducing the environmental impact of electronic devices [24], these approaches frequently involve bulky power sources or complex recycling processes that offer limited scalability. Consequently, there is a growing demand for innovative wearable ES devices that eliminate the need for external power supplies and additional components, making even the bulk of eco-friendly generators increasingly unacceptable.

This study proposes a fully textile-based wearable electrostimulation (WE-Stim) system that eliminates energy-harvesting components, focusing solely on delivering electrical stimulation. Recent research has shown that wireless energy transmission can be achieved using body-coupled (or mediated) energy transfer (BcET) systems [25–32]. Our previous studies demonstrated that BcET can harvest energy and form electric fields (EFs) within biological tissues, highlighting the potential for wireless electrical stimulation [28–31]. While earlier systems required additional devices and circuits for energy collection, WE-Stim overcomes these limitations by leveraging conductive and insulative materials in a novel configuration, enabling electrical stimulation without extra components or circuitry. Integrating WE-Stim technology into regular clothing allows for seamless electrical stimulation within wearable textiles without compromising mobility. Additionally, two physiological performance benefits were observed with WE-Stim: increased exercise performance and reduced delayed-onset muscle soreness (DOMS), along with a decrease in the width of thigh edema (WET) following exercise [33]. Through 3D simulation and experimental testing, we confirmed EF localization during activities such as walking, running, and using AC electronics, validating the concentration of EFs in targeted areas. We also demonstrated enhanced exercise persistence through electrical stimulation, highlighting the practicality and sustainability of WE-Stim in wearable applications.

2 | Integrating Wireless Electrostimulation into Commercial Clothing via BcET

The human body is continuously exposed to various forms of electromagnetic radiation, primarily from electronic devices such as smartphones and laptops connected to AC power sources. These devices operate using rectified energy derived from AC power, which incurs multiple energy losses during conversion, including conduction loss, reverse leakage, and parasitic capacitance (Figure 1a). These losses result in electromagnetic radiation that induces dielectric losses in nearby materials, further dissipating energy. Beyond the sinusoidal electromagnetic waves emitted by electronics, static electricity—produced through friction, such as between shoe soles and floors or between articles of clothing—generates non-sinusoidal electromagnetic radiation (Figure 1b).

These energy losses typically fall within the extremely low frequency (ELF) range, defined as frequencies below 1 kHz. Biological tissues at ELF frequencies exhibit exceptionally high relative permittivity [34], often exceeding 10^5 , allowing ELF energy to pass through the human body with minimal loss.

This property underpins the concept of BcET, where the human body serves as a medium for wireless energy transmission [26]. Previous studies have demonstrated that this transfer can produce localized concentrations of EFs, due to potential distortions in certain regions [28–31]. These findings laid the foundation for developing a wireless electrostimulation system through BcET, providing electrical stimulation without external power sources or complex electronics. In this study, we advance this concept by creating the first fully textile-based WE-Stim system. The design eliminates the need for any energy-generation components, allowing seamless integration with daily clothing (Figure 1c). The WE-Stim system consists of passive electrodes in contact with the body and counter electrodes, which together establish potential differences. As charges move between these electrodes to balance potentials, local potential distortions occur, concentrating EFs under the passive electrodes. This enables WE-Stim to deliver effective electrical stimulation without any electronic devices, batteries, or generators, marking a significant step forward in wearable electrostimulation technology.

3 | Textile-Based WE-Stim

The WE-Stim system can be seamlessly incorporated into commercial clothing using silver-coated nylon thread, a widely available conductive material. In this study, we employed basic stitching techniques commonly used in sportswear to create customizable electrode patterns, such as stripes, zig-zags, and cross designs (Figure 2a). These patterns can be tailored to fit specific muscle groups, allowing targeted electrostimulation while preserving the comfort and functionality of everyday wear. To demonstrate a practical application, WE-Stim was integrated into commercial athleisure wear using standard sewing techniques (Figure 2b). As illustrated, conductive threads are sewn onto the garment's inner side to make contact with the skin, while counter electrodes are positioned in non-contact areas, such as the waistband (Figure S1). This design ensures the conductive elements remain discreet, maintaining the clothing's appearance and comfort. A 4-thread overlock stitch—a durable, common textile construction technique—was used to secure the conductive patterns (Figure 2c). The WE-Stim leggings were fabricated using commercial conductive threads and subjected to simulated stability testing through repeated rolling and crumpling (Figure S2). Throughout these tests, resistance remained stable within approximately 15 Ω , even when the fabric was stretched up to 50% (Figure 2d). To confirm the durability and performance of WE-Stim garments, washing tests were conducted following international textile standards. After 30 wash cycles, the conductive threads displayed minimal variation in resistance, remaining within the stable range of approximately 15 Ω (Figure 2e). In addition, we investigated the effect of moisture on the electric field output by comparing dry and wet conditions. When the textile was wet, the electric field strength decreased, likely due to water interfering with the contact between the skin and the electrode surface. However, upon drying, the electric field strength returned to its original levels, demonstrating full functional recovery (Figure S3). These results demonstrate WE-Stim's robustness, ensuring sustained electrostimulation functionality even after extensive wear and washing.

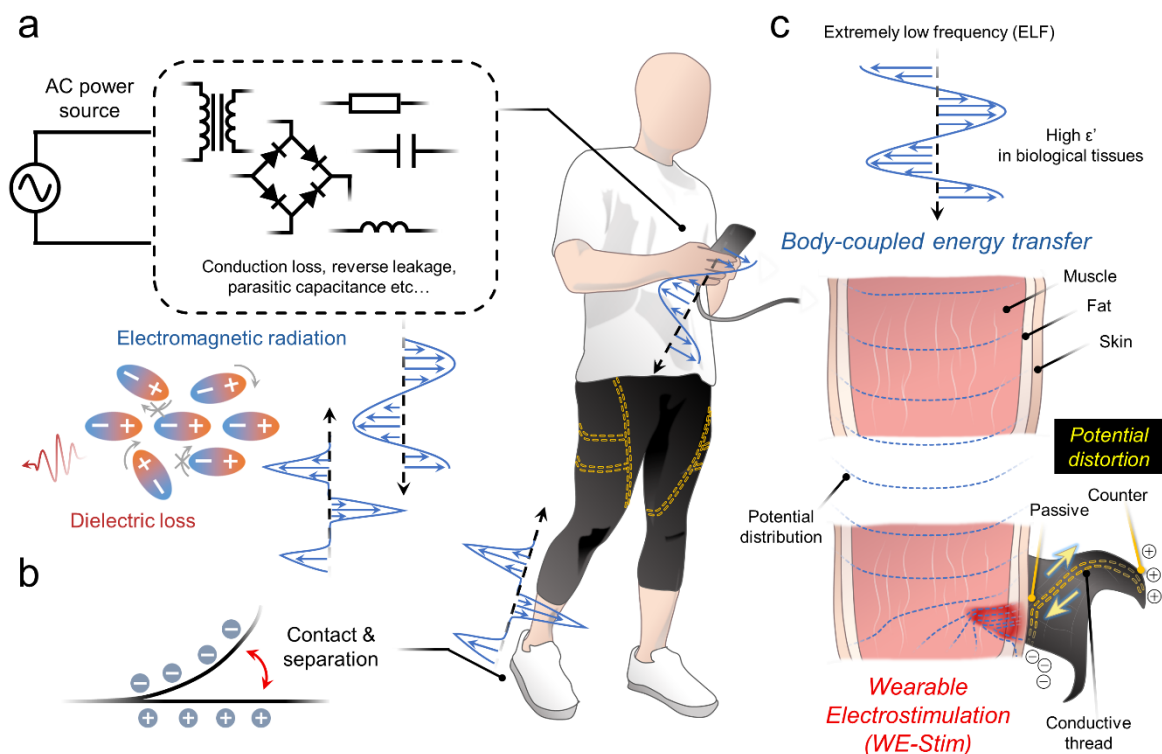


FIGURE 1 | Mechanism of BcET in wearable electrostimulation. (a) Energy losses occur during conversion from AC power sources in electronic devices, leading to electromagnetic radiation. (b) Frictional contact between surfaces, like shoe soles and floors, generates electrostatic charges, contributing to non-sinusoidal electromagnetic radiation during repetitive activities. (c) BcET harnesses the high permittivity of biological tissues at ELFs to transmit energy through the body, creating potential distortion and localized EF concentration.

4 | FEA Analysis for the WE-Stim Model

To visualize the WE-Stim mechanism, we used COMSOL Multiphysics with both AC/DC and electrical circuit modules to simulate EF concentration on the human body (Figure 3a; Figure S4). To mimic a person holding a smartphone and transferring ELF energy through the body, the simulation assumed a loss potential from the smartphone of approximately 100 V at 60 Hz (Figure 3b). The simulation compared EF concentration with and without the WE-Stim pattern. Without WE-Stim, the ELF potential traversed the body, concentrating EFs in regions with smaller cross-sectional areas, such as the wrist and ankle (Figure 3c). This EF concentration is primarily driven by the close proximity of input and ground, creating a strong potential difference due to the body's high permittivity, similar to the EDL phenomenon. Additionally, smaller cross-sectional areas increase flux, further amplifying EF concentration. When the WE-Stim pattern was applied, the electrode configuration induced local potential distortions, leading to concentrated EFs (Figure 3d). Grounding effects naturally lower potential in areas in contact with the ground, such as the feet (Figure 3e). As ELF potential decreases near grounded body parts, such as the face or opposite arm, placing electrodes perpendicular to this potential gradient intensifies distortion, creating stronger localized EFs (Figure 3f). To verify WE-Stim's effectiveness, we positioned electrodes along the thigh line, an area capable of generating higher EFs, and tested performance during thigh muscle exercises.

5 | Validation of WE-Stim: EF Strength

To validate the practicality and versatility of WE-Stim in real-world applications, we investigated the loss potentials generated from various physical activities and electronic devices (Figure 4a). For physical activities such as walking and running, we analyzed how different shoe soles and flooring materials affect the loss potentials, with activity frequencies ranging from 1 to 5 Hz to represent non-sinusoidal losses. The results showed that common materials, such as rubber and tile, generated relatively low loss potentials, typically between 10 and 20 V (Figure S5). However, using specialized materials like polytetrafluoroethylene or aluminum foil in shoe soles significantly increased the loss potential, with aluminum reaching nearly 200 V upon floor contact. This highlights the potential to enhance WE-Stim's effectiveness by customizing footwear materials. Beyond physical activities, we also examined loss potentials from common household electronics powered by AC, including laptops, tablets, and smartphones (Figures S6–S8). Devices from different manufacturers exhibited varying loss potentials; for instance, certain laptop adapters generated around 25 V, while some laptops emitted up to 150 V. Notably, certain devices exhibited minimal to no loss potential due to grounding or shielding systems. One laptop brand, for example, demonstrated a well-designed grounding system that significantly reduced the loss potential.

We measured the real-time EF generated by the WE-Stim during daily activities such as walking, touching electronics, and

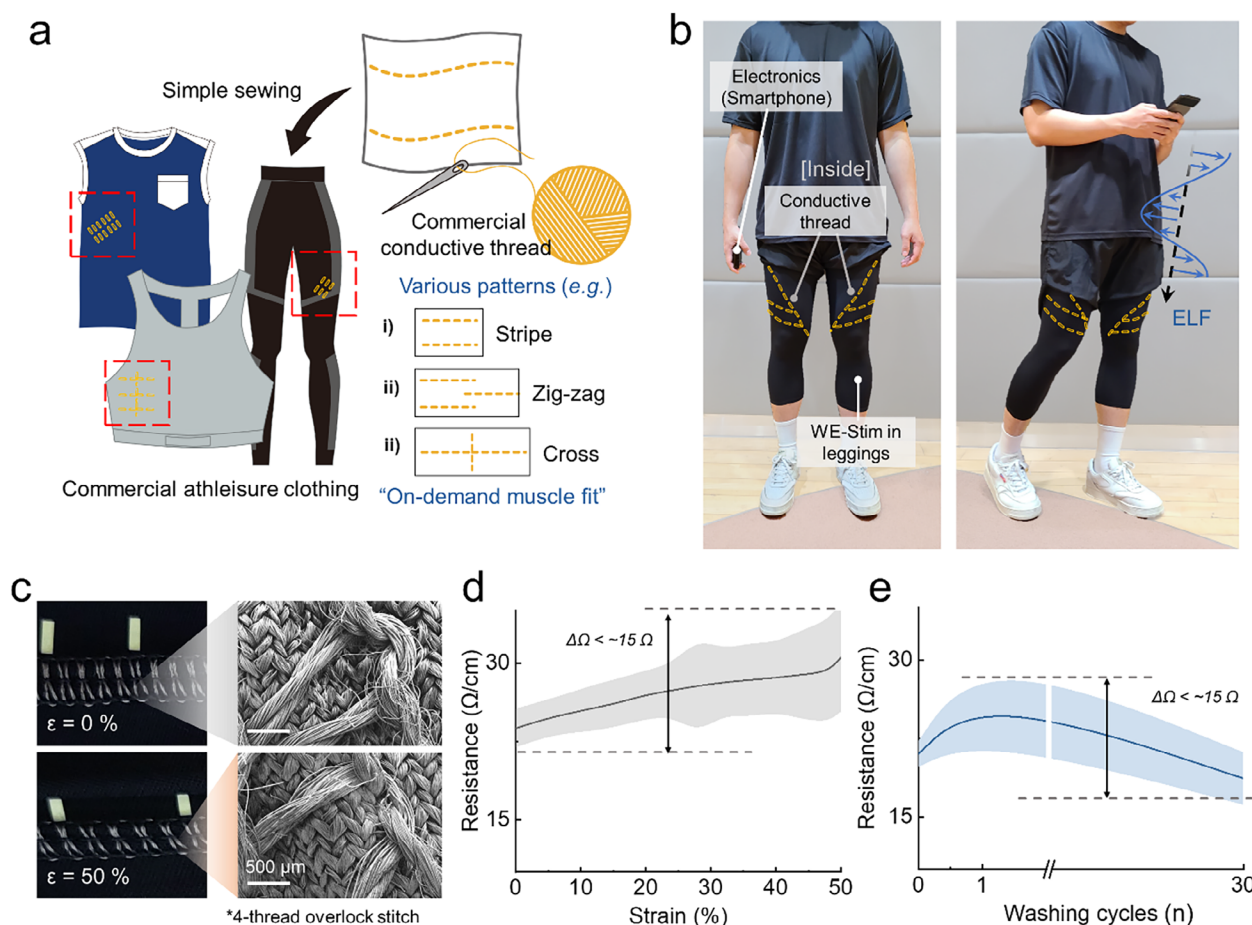


FIGURE 2 | WE-Stim integration with commercial clothing using conductive threads. (a) Various electrode patterns—such as stripes, zig-zags, and crosses—were created using simple sewing techniques with silver-coated nylon thread. (b) WE-Stim incorporated into athleisure wear. (c) Scanning electron microscopy images showing the durability of the conductive threads when stretched. (d) Conductive threads maintained stable resistance under strain. (e) The resistance changes after 30 washing cycles.

running (Figure 4b; Figures S9 and S10). To ensure accurate measurements that mirror real-life conditions, we employed a non-grounded method [35, 36], which avoids interference that grounding can introduce. Traditional grounded measurements, using tools like oscilloscopes or benchtop multimeters, often overestimate the EF due to grounding path influence, failing to reflect the actual conditions of floating electronics. By using the non-grounded method, we obtained more reliable, realistic data, showing the WE-Stim's performance under typical usage conditions. Our findings indicate that EF strength generated by the WE-Stim consistently increased with loss potentials from physical activities or interactions with electronics, demonstrating its capacity to stimulate biological tissues without external power sources (Figure 4c).

To further assess its practical application, we tested the WE-Stim athleisure in a gym environment, specifically measuring EF during the use of exercise machines (Figure 4d). Results showed a significant EF increase, especially when users maintained direct contact with the equipment, with EF strength reaching up to 4000 mV/mm (Figure 4e).

The primary advantage of the WE-Stim is its capability to generate EFs without the need for additional batteries, generators, or

devices, enhancing both energy efficiency and enabling diverse, on-demand EF generation across various environments. To further highlight WE-Stim's unique advantages, especially its ability to generate electric fields without any powered electronic hardware, we introduce a supplementary figure of merit, the energy efficiency factor (EEF). This metric enables a unified quantitative comparison across diverse stimulation platforms, including powered, nanogenerator-based, and hardware-free systems. Traditional electrical stimulation methods—such as neuromuscular electrical stimulation, transcutaneous electrical nerve stimulation, and functional electrical stimulation—rely on direct power sources, which allow more versatile field energy utilization. However, these systems tend to have lower EEF and higher device weight, limiting their overall practicality [37, 38]. Typically, traditional commercial methods show EEFs ranging from 10^3 to 10^4 (Figure 4f). The EEF is calculated as follows:

$$EEF = \frac{(EnergyTransferDistance + 1 [mm])}{(PowerConsumption + 1 [W]) \times (DeviceVolume [mm^3])} \times [1000] [W] [m^2]$$

In this formula, energy transfer distance is treated as a positive factor, reflecting effective energy transfer and convenience, while

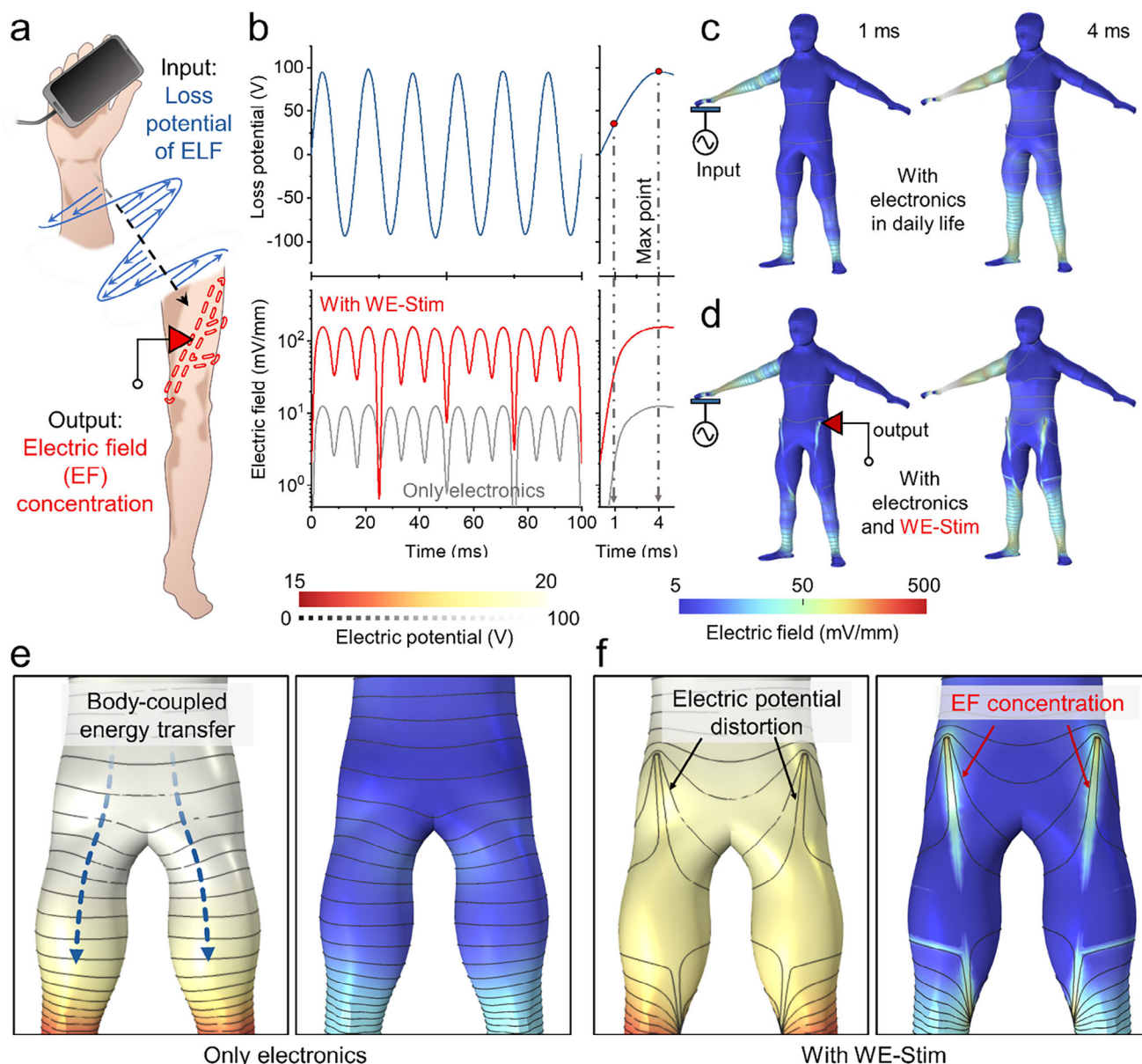


FIGURE 3 | FEA analysis for the WE-Stim. (a) Loss potential of ELF input, triggered by holding a smartphone, conducted through the body from the right hand, with the WE-Stim's patterned electrode positioned on the left thigh. (b) Time-based input and output variations in the FEA model. (c,d) EF concentration comparison with and without the WE-Stim at intervals of 1 and 4 ms. (e) Potential distribution across body areas in contact with the ground, with grounded regions (e.g., feet) displaying reduced ELF potential toward the ground. (f) Electrode placement perpendicular to this gradient increased potential distortion, amplifying EF strength.

power consumption and device volume are negative factors, as they increase energy demand and decrease practicality. The EEF was calculated based on typical reported parameters for commercial neurostimulation devices, including power consumption (0–30 W), device volume (50–4 751 040 mm³), and stimulation range (a few to tens of millimeters). To ensure comparability across systems and avoid undefined results (e.g., zero volume or power), a constant of 1 was added to each variable. While recent advances in battery-free, nanogenerator-based electrical stimulation technologies show promise, their EEF remains lower than WE-Stim's [39–44] (Table 1). Additionally, in cases where EEF is comparable, the effective field range is significantly constrained. While the hardware-free and self-sustained nature of WE-Stim is its core strength, the EEF metric provides an

objective way to benchmark its performance against both conventional and emerging stimulation technologies. Our analysis shows that WE-Stim surpasses not only traditional powered devices but also recent battery-free, nanogenerator-based systems in terms of energy efficiency and effective field generation, making it a highly practical and versatile solution for wireless stimulation.

6 | Validation of WE-Stim: Increased Exercise Performance and Muscle Relief

In the previous section, we described how wearing WE-Stim leggings transmits AC electrical energy, which is typically

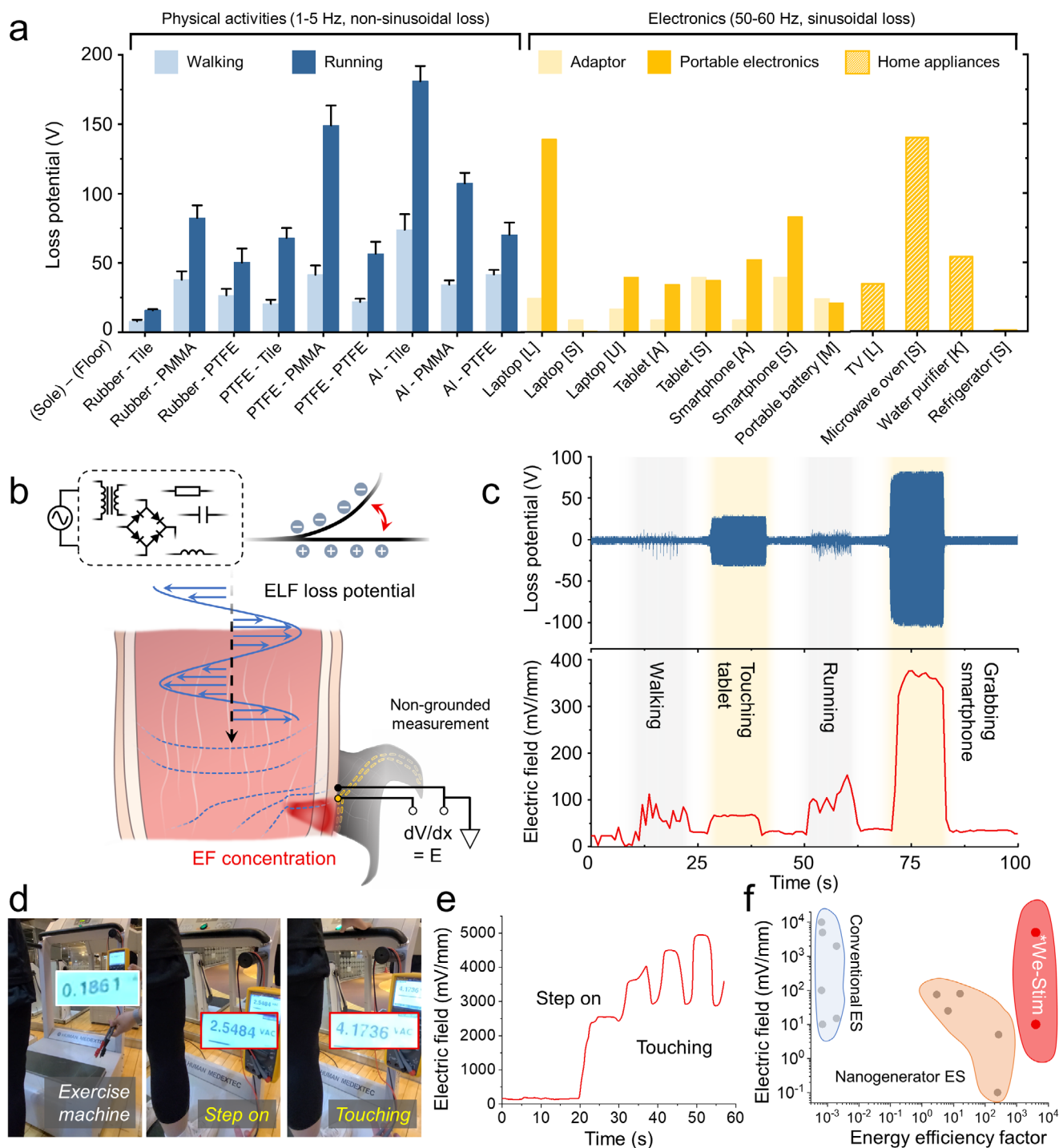


FIGURE 4 | Energy source types and EF strength of WE-Stim in practical conditions. (a) Loss potentials from various physical activities and electronic devices, with physical activity frequencies between 1 and 5 Hz and electronic devices typically operating at 50–60 Hz. (b) Diagram illustrating loss potential and EF generation when the WE-Stim operates in an ungrounded setup. (c) Real-time tracking of loss potential and EF strength across activities like walking, tablet interaction, running, and phone handling. (d) Experimental validation within a gym environment. (e) Enhanced EF strength (up to 4000 mV/mm) observed with exercise machines in use with the WE-Stim. (f) Comparative analysis of EEF.

generated and lost in daily activities, through the BcET system. The WE-Stim delivers low-frequency electric fields based on the hypothesis that modulating the muscle microenvironment—without triggering direct excitation—can mitigate fatigue and facilitate faster recovery. This form of stimulation does not cause noticeable contraction or discomfort but is designed to

support muscle restoration and functional performance during and after exercise. Our approach stands apart from conventional neuromuscular or spinal stimulation strategies, which aim to induce strong excitatory responses and operate via distinct physiological mechanisms [31, 45]. Based on previous studies, we expect that the improvements in muscle function could be

TABLE 1 | Energy efficiency factor of electrical stimulation systems.

Type	Energy Transfer Distance (mm)	Power Consumption (W)	Device Volume (mm ³)	Refs.
Conventional	0	30	170 × 190 × 60	[37], RehaStim 2
Conventional	0	6	280 × 202 × 84	[37], 906A Premier
Nanogenerator	5	0	15 × 15 × 1	[38]
Nanogenerator	0	0	41 × 49 × 1.7	[38]
Nanogenerator	0	0	1 × 50 × 1	[38]
Nanogenerator	30	0	0.5 × 50 × 50 × pi	[38]
Nanogenerator	0	0	50 × 20 × 1.5	[38]
WE-Stim	1000	0	0.1 × 50 × 50	—

induced due to two main mechanisms. First, the electric field may facilitate muscle fiber activation by altering transmembrane potential, enhancing ion channel sensitivity, and promoting ATP production, cell proliferation, and differentiation. In addition, increased expression of muscle growth markers such as MyoD and myogenin further supports this effect [46–52]. Second, the electric field may enhance neuromuscular junction (NMJ) function by promoting acetylcholine receptor clustering, improving signal transmission from motor neurons to muscle fibers [53, 54]. These combined mechanisms, rather than direct muscle contraction, likely explain the functional benefits observed with our electric field-stimulating leggings. In this study, we investigated whether wearing WE-Stim leggings would have positive effects on exercise performance, recovery, and DOMS (Figure 5a). In this study, the WE-Stim electrodes were specifically positioned on the anterior thigh (Figure S1), allowing for targeted stimulation of the quadriceps. The exercises selected—leg extensions and step-ups—were chosen to evaluate functional improvements in this muscle group. For the human physiological performance test, WE-Stim leggings were prepared using both conductive and non-conductive threads, randomly assigned to the left and right sides. To implement a stable and user-friendly electrical stimulation, a charging smartphone was used as the energy source. This study is based on the hypothesis that applying a low-frequency electric field can modulate the muscle microenvironment, reduce fatigue, and accelerate recovery, ultimately improving physical performance. To examine post-exercise recovery effects, participants were instructed to use their smartphones for a fixed time during resting periods. This naturally triggered electrical stimulation through the leggings during typical recovery behavior, enabling passive and repeatable stimulation without the need for additional equipment or intervention. Prior to discussing the results, we considered it important to clearly describe the experimental conditions. Unlike conventional neuromuscular stimulation, which often causes noticeable sensations, the electric field (EF)-based stimulation used in this study works below the sensory threshold and does not stimulate skin receptors. This allowed participants to remain effectively blinded without needing a separate sham or placebo condition. None of the participants reported feeling the stimulation or identifying the treated leg. Electrical perception thresholds generally begin at approximately 3.5 mA [55, 56], corresponding to an electric field intensity of approximately 3500 mV/mm or higher, considering skin impedance ranges (5–20 kΩ) at frequencies below

2 kHz [57]. This relationship is expressed by the following equation:

$$E = \frac{I \times R}{d}$$

E indicates electric field, I indicates current, R indicates impedance of skin and d indicates distance between stimulation electrodes. In contrast, our EF-based system generates significantly lower electric fields (< 400 mV/mm, Figure 4c) using smartphones, inherently ensuring no detectable sensations. The timeline for the human physiological performance test is provided in the supplementary information (Figure S11).

The physiological performance test aimed to evaluate the effectiveness of WE-Stim leggings. Six participants were recruited to perform two specific exercises, leg extensions, and step-ups, with each exercise completed in three sets per leg (Figures S12–S14). Performance was quantified as the maximum number of repetitions performed per set by each participant. The values were normalized to the maximum number of repetitions performed on Day 1, allowing us to track day-to-day changes in performance. A detailed four-day protocol (Day 0 to Day 3) is described in the Experimental section. Exercise performance was primarily assessed through leg extension tests (Figure 5b,c). The total average performance across all sets was initially assessed on days 1 and 2, showing an approximately 11% increase when participants wore WE-Stim leggings (Figure 5d; Figure S15). This improvement is attributed to reduced muscle fatigue and enhanced muscle fiber activation from electrical stimulation. To validate these results comprehensively, performance was further analyzed by day and by individual set, using the gap in the number of exercises performed per set as a metric. Participants wearing WE-Stim consistently showed performance increases across all sets, with performance in the final set on day 2 exceeding twice that of the control group (Figure 5e; Figure S16). This improvement aligns with the WE-Stim's role in promoting muscle fiber activation through targeted electrical stimulation.

Another key factor influencing exercise performance is the presence of edema and DOMS, as excessive edema and high DOMS during exercise can decrease performance due to pain. Thus, reductions in DOMS and WET were measured when the WE-Stim was worn. The average thigh circumference, used as an indicator

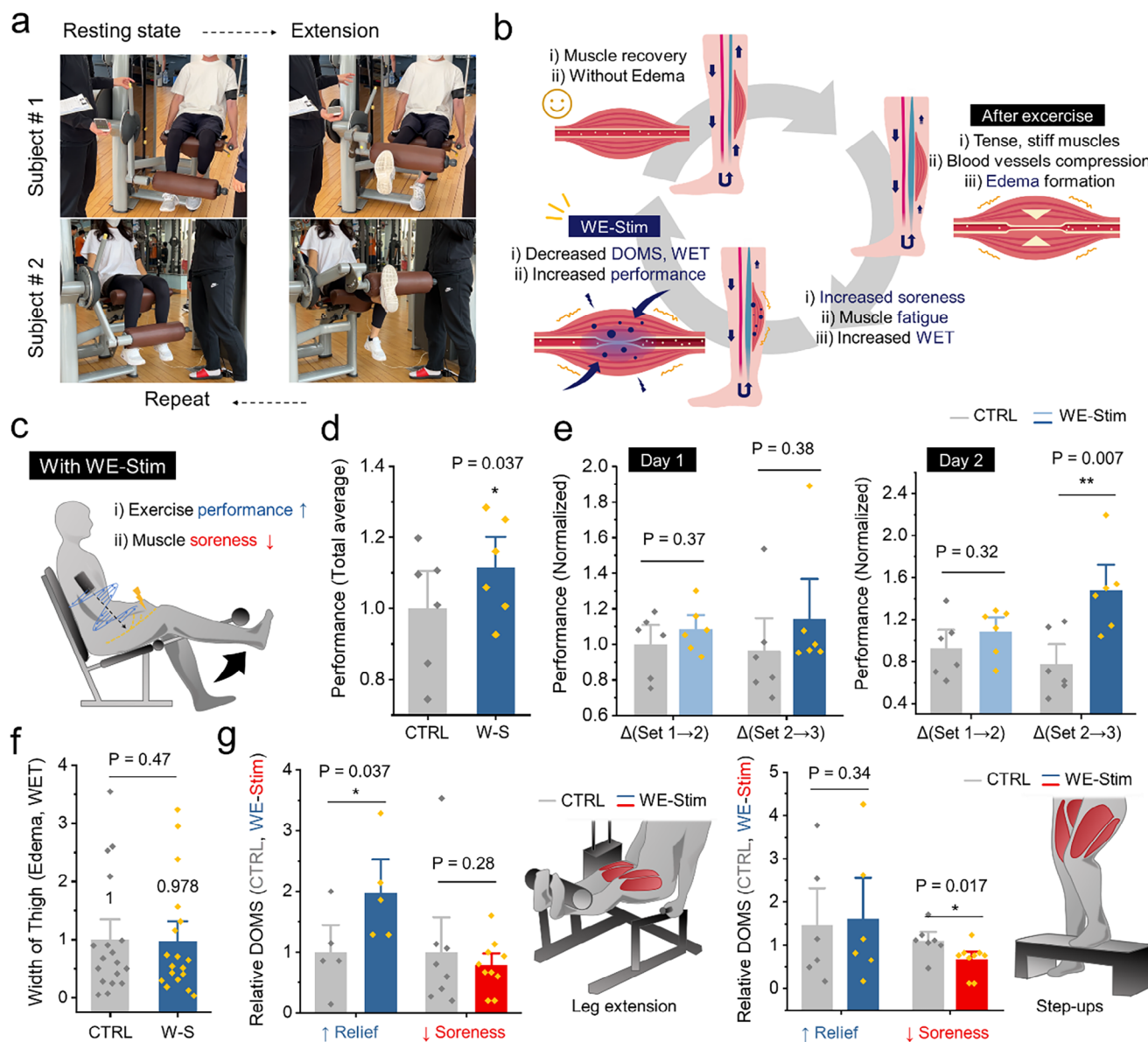


FIGURE 5 | Physiological performance evaluation of WE-Stim. (a) Image showing the leg extension test in the physiological performance study. (b) Illustration depicting reduced DOMS, reduced WET, and enhanced exercise performance with WE-Stim. (c) Diagram of the leg extension exercise performed with WE-Stim. (d) Increase in overall average exercise performance with WE-Stim use ($n = 6$). (e) Daily work performance data ($n = 6$). (f) Average WET data across subjects ($n = 18$). (g) Relative DOMS data after leg extension (left, Relief: CTRL $n = 5$, WE-Stim $n = 5$; Soreness: CTRL $n = 8$, WE-Stim $n = 10$) and step-up exercises (right, Relief: CTRL $n = 6$, WE-Stim $n = 6$; Soreness: CTRL $n = 7$, WE-Stim $n = 9$) with WE-Stim. Data are presented as mean $\pm$ standard deviation for each group. * $P < 0.05$, ** $P < 0.01$ (One-way ANOVA with Tukey's correction; all experiments were conducted independently).

of WET, showed a slight decrease in the group wearing WE-Stim leggings; however, this change was not statistically significant (Figure 5f). Additionally, DOMS in the thigh muscles post-exercise was evaluated for each participant (Figure 5g; Figure S17). In this analysis, muscle relief is marked in blue, while increased soreness is shown in red (Figure 5g). We separated muscle relief and soreness because participants evaluated not only changes in soreness but also the degree of muscle comfort during the DOMS assessment. The evaluation was conducted following both leg extension and step-up exercises. As a result, the use of WE-Stim leggings showed an increase in muscle relief after the leg extension test and a reduction in muscle soreness after the step-up

test, suggesting that WE-Stim effectively reduced muscle fatigue and DOMS while enhancing exercise performance.

Overall, these results demonstrate that by applying the conductive thread structure to various sports or athleisure wear, it is possible to achieve targeted muscle and skin stimulation without external power sources or wiring. Additionally, this study's findings support the design and customization of other WE-Stim systems for specific exercises, providing on-demand electrical stimulation. This WE-Stim technology could potentially be extended to new applications in sportswear.

7 | Conclusions

This study presents WE-Stim, an innovative, textile-based wearable electrostimulation system that integrates electrical stimulation seamlessly into regular clothing. This first-of-its-kind leggings-based system employs a unique design with conductive threads and insulating materials, enabling effective electrical muscle stimulation. The generation of EFs through body contact with the electrical wiring was confirmed by FEA, and physiological performance tests demonstrated that EFs were produced not only during various exercises but also through contact with electronic devices. These tests further revealed that electrical stimulation effectively reduced DOMS and enhanced exercise efficiency during and post-exercise. The stimulation characteristics may vary depending on the type of energy source—such as static electricity or contact-induced charge—and proximity to powered electronic devices is required for consistent BcET activation. Nevertheless, the human body is already surrounded by electromagnetic fields in daily life, it can excess the utility of WE-Stim. A key feature of WE-Stim is its versatility: while it currently provides electrical stimulation through leggings, the application of conductive threads and specialized conducting and insulating materials makes it adaptable to regular leggings and other clothing types, allowing virtually any garment to be converted into a WE-Stim. We are confident that the BcET system and WE-Stim concept will drive advancements in wearable technology. This study represents the first demonstration of wearable, fabric-based electrical stimulation that clinically improved recovery from fatigue and enhanced exercise performance. We anticipate this system to inspire further integration of energy-harvesting textiles in medical and sports technologies.

8 | Methods

8.1 | Finite Element Analysis (FEA) Simulation

EF simulations for the WE-Stim system were conducted in COMSOL Multiphysics using a 3D model. In these simulations, the passive electrode was configured to align along the thigh, remaining in direct contact with the skin. Floating potential conditions were applied to allow the passive electrode to act as an electrode [28, 31]. The counter electrode, positioned at the waist in a configuration matching the actual WE-Stim, was modeled with dimensions of 2.5 cm in length and 0.5 cm in width. To avoid interference with the mesh, the counter electrode was positioned 1 mm away from the skin. A 100 V, 60 Hz AC potential was applied to the right hand. The simulation was conducted as a time-dependent analysis over a period of 0–0.1 s with a time step of 1 ms. The governing equation for the system is:

$$-\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = \delta$$

This configuration reveals how energy is distributed through the body and illustrates the concentration of EF under the passive electrodes. The high relative permittivity of the human body ($\epsilon_r = 10^7$) maintains the electric potential, enabling efficient energy transfer. The simulation illuminates how potential distortions are formed under the passive electrodes and the concentration of EF.

8.2 | Physiological Performance Test Protocol

After reviewing the physiological performance study, six healthy volunteers (mean age = 23.5 years, 50% male) were recruited and provided consent to participate in a human physiological performance test. The tests were conducted over four consecutive days, from Day 0 to Day 3. All performance, DOMS, and WET assessments were carried out at the same time each day (12 PM) to minimize diurnal variation. Before the tests, participants were instructed to refrain from strenuous exercise and alcohol consumption throughout the experimental period. To control dietary intake, they were also asked to consume a consistent amount of protein with every meal. Also, each participant's body composition (measured using InBody) was recorded. Based on the InBody results, participants' hydration levels were maintained within a similar range, with intracellular water content between 15 and 18, and extracellular water content between 9 and 11. Then, participants' WET, DOMS, and one-repetition maximum (1RM) were measured before the experiment, and the tests were conducted after a sufficient rest period of two days. The physiological performance test adhered to stringent protocols. Based on each participant's 1RM, the exercise load was set to 60% of their individual 1RM. Participants then performed the leg extension exercise to their maximal voluntary capacity at this 60% load, and this procedure was repeated for a total of three sets. Due to the individualized load normalization, the number of repetitions completed within each set naturally varied among participants; however, this approach ensured that all participants exercised at a comparable relative intensity. For the step-up exercise, the maximal number of repetitions that each participant could perform was considered equivalent to their individual 1RM capacity for that movement. Participants then performed the step-up exercise accordingly. For data analysis, the maximal number of repetitions completed during the first set was used as each participant's baseline, and subsequent performance outcomes were normalized relative to this value. During the exercises, they wore WE-Stim leggings and an armband with a charging smartphone, performing each exercise to their maximum capacity. Following the exercise session, participants continued wearing WE-Stim leggings and took a 1-h break while using their smartphones at two intervals: 3 and 8 h post-exercise. On the second day, body composition, WET, and DOMS were reassessed before participants repeated the same exercise and rest protocol from day one. On the third day, no additional exercises were conducted, and only WET and DOMS measurements were taken. After DOMS measurement, participants completed two additional 1-h rest sessions, totaling 2 h. Final measurements of DOMS and WET were taken the following day, concluding the physiological performance test. To control for bias and objectivity, conductive threads were not applied to one leg of the WE-Stim leggings, allowing the BcET-based electrical stimulation to target only the other leg. Furthermore, participants were not informed which leg received the BcET system during the test.

8.3 | Electrical Stimulation Protocol by WE-Stim Leggings

Electrical stimulation was applied continuously throughout the exercise sessions, beginning at the start of exercise and continuing until all sets were completed. Additional post-exercise

stimulation was administered for 1 h at 3 h and 8 h after the exercise session to facilitate recovery. On the first and second days, stimulation was applied continuously during the exercise sessions, and additionally for a total of 2 h during the post-exercise rest periods. Therefore, the total stimulation time per day exceeded 2 h when including both the exercise and recovery phases. On the final day, electrical stimulation was applied for 2 h in the absence of exercise. For clarity, the detailed procedure of the electrical stimulation protocol is provided in Figure S11.

8.4 | Statistical Analysis

Statistical analysis was performed using OriginPro with a significance level of 0.05, employing one-way ANOVA with the Tukey method. Data are presented as mean $\pm$ standard deviation for each group. * $P < 0.05$, ** $P < 0.01$, and all experiments were conducted independently.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: aenm70565-sup-0001-SuppMat.docx