An Open-Source Vibrotactile Vest Design for Personalized Rhythmic Sensory Input

Gabriela Franco[1], Peter Lin[1], Emily Liu[1], Selim Uzgoren[1], Abhinav Vetcha[1], Jonathan T. Pierce[2,3], and Audrey C. Brumback[3,4,*]

[1] Department of Biomedical Engineering
[2] Department of Neuroscience
[3] Center for Learning and Memory
[4] Departments of Neurology and Pediatrics at Dell Medical School
The University of Texas at Austin, Austin, Texas USA
*Corresponding author: audrey.brumback@austin.utexas.edu

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This work does not involve human subjects (or procuring human tissue from human subjects) or animal study.

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Key words: wearables, vibrotactile, repetitive behavior, stimming, stereotypy, intellectual disability, autism spectrum disorder

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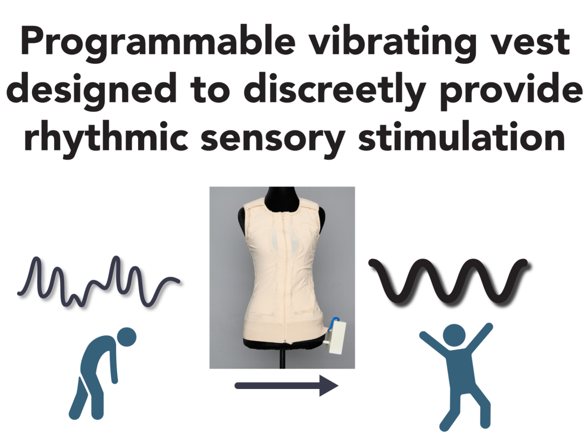
ABSTRACT

Stereotyped rhythmic movements (commonly referred to as “fidgeting,” “stereotypies,” or “stims”) are often used by individuals to support sensory and emotional regulation, enhance focus, and reduce stress. The therapeutic benefit of these movements is at least partially due to the rhythmic sensory experience generated by the movements. However, stereotyped movements can be inconvenient to engage in, or even harmful in certain contexts. To address this, we developed a discreet, wearable vest that passively delivers rhythmic sensory input through vibrating coin motors embedded between layers of fabric. Designed to be worn under clothing, the vest allows users to control vibration frequency and duty cycle via a Bluetooth-enabled smartphone app, enabling personalized optimization. The device is rechargeable and operates at full power for up to four hours. We quantified vibration pressure, signal frequency, duty cycle, battery life, noise level, and temperature. Results indicate that the device accurately maintains frequency and duty cycle within acceptable error margins and meets all engineering specifications except for battery life. All design elements and source code are openly available, allowing others to replicate or modify the device for their own use. Future work will be needed to evaluate the vest in real-world settings for safety, efficacy, and regulatory compliance.



INTRODUCTION

Repetitive, non-goal-directed movements such as foot tapping, pen clicking, and rocking are common across neurotypical and neurodivergent populations. These stereotyped behaviors—often referred to as "stimming" or "fidgeting"—are reported to improve focus, regulate sensory input, and reduce stress. In individuals with autism spectrum disorder (ASD) and attention deficit / hyperactivity disorder (ADHD), stereotypies are particularly prevalent [1–3], and may serve important self-regulatory functions [4–6]. Fidget spinners have been marketed for use in the classroom to reduce symptoms of inattention and hyperactivity, but their use is not supported empirically [7].

The positive aspects of motor stereotypies are tempered by the potential negatives such as risk of injury [8–11] and risks of accidental ingestion of fidget spinners, particularly for younger children and those with intellectual disabilities [12]. Fidgeting can trigger discomfort in people with misokinesia sensitivity, a common trait in which the sight of others fidgeting elicits a negative emotional responses [13] and has the potential to be distracting to classmates. Alternative methods for providing rhythmic input to the brain could potentially provide the benefits of stereotypies without the need to engage in repetitive movements.

How repetitive movements and the resulting rhythmic sensory signals might improve brain function is an area of increasing interest. Well-timed brain rhythms are necessary for effective sensory processing and attention [14,15]. One possibility for how performing stereotyped movements might benefit people with autism [16] or ADHD [17] is that the rhythmic motor signal and/or the rhythmic sensory feedback produced may entrain brain rhythms (**Fig. 1**) and thereby improve focus and sensory processing [6]. If rhythmic sensory signals caused by the movements is part of the beneficial mechanism, providing rhythmic sensory inputs exogenously could produce the benefit of stereotypies without the need for the movements themselves. Massage pillows, sensory pads, vibrating toys, and other vibration therapies are described as calming [18–20]. Full-body vibration and vibroacoustic music may decrease the frequency of some stereotypies in people with autism [21,22] and have been used to regulate respirations in premature infants [23] . However, besides being inconvenient, there may be health drawbacks to using whole-body vibration therapy for extended periods [24]. Weighted compression vests and inflatable deep pressure vests have been used to provide a sense of comfort to clinical and non-clinical populations [25]. There are various other weighted products available such as weighted blankets [26] for similar purposes.

Here we present the prototype of a vibrating vest intended to inconspicuously provide rhythmic sensory input to the body. The vest combines compressive pressure [27] with customizable vibrotactile stimulation and is designed to be worn under clothing. Importantly, all design files and source code are openly available, allowing others to replicate, modify, and build upon our work. This open-source approach aims to foster innovation and accessibility in assistive technology for individuals who benefit from rhythmic sensory input. This manuscript reports technical characterization of the prototype only; human usability and efficacy testing have not yet been conducted, and therapeutic claims remain hypothetical pending clinical validation. Future studies are planned to test the efficacy and iterate the design based on feedback from users.

Please note, this device should only be used with the informed consent of the wearer and must never be used as a restraint, punishment, or a negative consequence for behaviors. The user should maintain full autonomy and control over the device, including the ability to remove it at any time. Use of this device should be voluntary, respectful of user's dignity, and prioritize the individual's autonomy and well-being [28,29] .

METHODS

Overview

Our design is a combination of two existing methodologies that have been studied to reduce stereotypy intensity and frequency: compressive deep pressure vests [30] and vibration therapy [22,31]. Our solution is a vibrating compressive vest with small vibration motors distributed along the back, chest, and shoulders to stimulate a large surface area (**Figs. 2 and 3**). Vibration frequency and duty cycle are adjustable in real time through a smartphone application (**Fig. 7**) to meet the user's preferences and immediate needs. A zipper allows the vest to be easily and quietly put on and taken off. In addition to vibration, the vest also uses elastic compressive material to provide snug compressive pressure to the user's torso. The vest is thin enough for the user to wear under normal clothing and has minimal noise levels during operation, making it a discreet solution. An electronics holster houses the Arduino Uno microcontroller, batteries, and Bluetooth module. In its current form, the holster is bulky, but with future versions, its size can be minimized.

Design Principles and Engineering Specifications

This vest was designed to balance functional performance with user experience, guided by seven core design principles: it had to be effective in delivering vibrotactile input, discreet, intuitive to operate, durable across varied environments, portable for daily use, affordable for broad accessibility, and comfortable for extended wear. These principles informed specific design criteria, including comfort and non-stimulatory feel when inactive, user safety, ease of operation, and a discreet form factor. Additional desirable features included deep pressure capability for calming effects, broad surface area coverage, long battery life, robust construction, and adjustable sizing.

To meet these goals, we established engineering specifications with measurable targets: vibration pressure of approximately 100 Pascals (Pa) across a frequency range of 1–100 Hz, fully adjustable duty cycles (0–100%) to accommodate individual preferences, minimum 5-hour battery life for portability, operational noise below 20 decibels (dB) for discretion, and surface temperature under 43°C for safety and comfort. The device weight was kept under 1 kg to ensure wearability. These specifications aim to maximize the likelihood that the device can be seamlessly integrated into users' daily lives (see **Table 1** for summary of performance against targets).

All design files and source code are openly available, enabling others to build, modify, and improve upon the device to suit their own needs.

Hardware

The foundation of the vest is a compression vest made of a stretchy, breathable material with a zipper through the middle that ensures ease of wear. The vest has 18 embedded coin vibration motors (8 mm in diameter; 3 Volt (V) Direct Current (DC) power): upper chest (4), shoulders (4), lumbar (2), and trapezius (8; **Fig. 3**). The number of motors in our prototype was limited by budgetary and pandemic-related supply chain constraints and technical limitations of the microcontroller (number of pins). Motors are spaced approximately 1–2 inches apart to maximize surface area stimulated. The coin motors and wires are attached to the vest using hook-and-loop fasteners and covered with a glued-on cloth layer so that neither is in direct contact with skin.

Wires and additional components are housed in a package disguised as a Leatherman-like holster (**Fig. 4**) connected to the bottom of the vest and attached to the user's belt. The holster is a 47 × 77 × 122 millimeter (mm), 3-dimentional (3D)-printed polylactic acid box with a loop for attachment to a belt. The sliding lid of the box has a rectangular notch to accommodate for wire routing from the vest and a sliding switch. The box contains bulkier components that do not fit well on the vest, such as the batteries, Bluetooth module, microcontroller, sliding switch, and first nine transistors of each Darlington pair.

Electronics

Coin vibration motors are controlled by an Arduino Uno microcontroller and 18 Negative-Positive-Negative (NPN) transistors arranged as Darlington pairs. The microcontroller is connected to an HC-05 Bluetooth module, which receives information from a smartphone application to allow the user to control the motor groups, adjusting the duty cycle and vibrational frequency of pairs of coin motors. A circuit diagram of the prototype is given in **Fig. 5**. The device is powered by two nickel metal hydride batteries with a combined capacity of 4,000 milliampere-hours (mAh) with voltage outputs of 4.8 V.

Software

The prototype is controlled by software on an Arduino Uno microcontroller (Flow charts in **Fig. 6**. Code **Supplemental Materials**). The Arduino receives messages from a mobile phone application via an HC-05 Bluetooth module and controls the motor groups accordingly. After initialization, the Arduino enters the main loop (**Fig. 6, top**), wherein it repeatedly checks whether a Bluetooth message has been received. If so, the Arduino parses the message and adjusts the on/off state, frequency, and duty cycle of each motor group accordingly. The frequency ranges from 1 to 100 Hertz (Hz) (inclusive) at 1 Hz intervals, and duty cycle ranges from 0% to 100% (inclusive) at 1% intervals.

The frequency and duty cycle of the motor groups are controlled with a 1 kHz interrupt service routine (ISR flowchart in **Fig. 6, bottom**). Every time the interrupt is triggered, the Arduino checks whether any of the motor groups need to be turned on or off. It does this by keeping track of a list of times (in ms) until each group needs to be toggled. When any time reaches zero, the Arduino will toggle the associated motor group and recalculate the time depending on that group's frequency and duty cycle.

Phone Application

The user interface is an Android phone application with a single scrolling screen (**Fig. 7** and **Supplemental Materials**). It has a button at the top where the user can select the HC-05 Bluetooth module to connect to. It has a visual representation of the locations of the motor groups on the chest, shoulders, and back that the user can click to turn on and off. Users can click and hold on one of the buttons to change the frequency and duty cycle of that single motor group or click the button "Change All Motors Vibration Speed" to control the frequency and duty cycle of all the motors at once.

Once the motor group(s) are selected, the user can scroll down to the bottom of the screen to modify frequency and duty cycle using two sliders. These sliders allow for adjustment between 1 and 100 Hz for frequency and 0% to 100% for duty cycle and display the exact values of the sliders via labels that are constantly updated below them. Another label above the frequency slider indicates which motor region's attributes are currently being modified.

Any time the motor groups, frequency, or duty cycle are changed, the application sends new user input data to the Arduino via the HC-05 Bluetooth module to apply the changes in real time so the user can quickly determine what settings they prefer.

RESULTS

We conducted comprehensive testing of the prototype's technical performance across all engineering specifications. **Table 1** summarizes the results, showing that the device met 7 of 8 target specifications.

Table 1. Summary of Engineering Specifications and Performance

Parameter	Target Specification	Achieved Performance	Met Target?
Weight	<1 kg	750 g	✓ Yes
Vibration Pressure	≥100 Pa	138 Pa	✓ Yes
Frequency Range	1-100 Hz	1-100 Hz (error <1%)	✓ Yes
Duty Cycle Range	0-100%	0-100% (error <2%)	✓ Yes
Battery Life	≥5 hours	3.95 hours*	✗ No
Noise Level (covered)	<20 dB	5 dB	✓ Yes
Surface Temperature	<43°C	<30°C	✓ Yes

**Calculated at 100% duty cycle for all motors; practical use expected to exceed 5 hours.*

Weight

The device weight was measured by placing all components (the vest with all electronics attached and the 3D-printed holster) into a plastic bag and weighing it on a spring scale. The result was 750 g, which meets our goal of <1 kg.

Vibration Pressure

We measured the peak pressure of the coin motors using a force-sensitive resistor (FSR; code in **Supplementary Materials**). First, a baseline pressure was applied by pressing the FSR against a coin motor. Then, the motor was turned on at 1 Hz frequency and 50% duty cycle. This resulted in a square-wave pressure signal from which the baseline pressure was subtracted (**Fig. 8**). The resulting peak pressure was 0.02 lbf/in², or approximately 138 Pa, meeting our requirement of at least 100 Pa, which is the typical vibration pressure amplitude of a smartphone.

<u>Frequency</u>

The vibration frequencies of the motors must accurately match user-selected settings. The target range of 1–50 Hz was extrapolated from previous studies on vibration therapy [21,22]. To test the accuracy, the prototype was set to various frequencies while at 50% duty cycle, and the motor control pin on the Arduino was sampled over a period of 3 seconds. The frequency of the signal was calculated in MATLAB using fast Fourier transforms (code in **Supplementary Materials**). The percent error never exceeded 1%, indicating an accurate frequency response (**Table 2, top**).

<u>Duty Cycle</u>

A variable, user-defined duty cycle was also important to personalize the stimulation to optimize comfort. To test the accuracy of responses to changes in duty cycle, the prototype was set to a series of duty cycles at 1 Hz frequency, and the motor control pin on the Arduino was sampled over a period of 3 seconds. The duty cycle was estimated by calculating the area under the signal curve (**Table 2, bottom**). The percent error never exceeded 2%, indicating an accurate duty cycle response.

Frequency		
Programmed (Hz)	Measured (Hz)	% error
1	1.0013	0.130
2	2.0027	0.135
5	5.0067	0.134
10	10.013	0.130
25	25.033	0.132
50	49.733	-0.534

Duty Cycle		
Programmed (%)	Measured (%)	% error
5	4.94	-1.200
25	24.87	-0.520
50	50.15	0.300
75	75.08	0.107
95	94.93	-0.074

Table 2. Frequency (top) and Duty cycle (bottom) accuracy were within target ranges.

<u>Battery Life</u>

The battery life is a critical specification for wearable devices intended for daily use. We calculated the theoretical battery life based on component specifications as follows:

Variable Definitions:

- V = voltage (volts)
- I = current (amperes)
- P = power (watts)
- C = battery capacity (milliampere-hours, mAh)
- E = energy storage capacity (watt-hours, Wh)
- t = battery life (hours)

Power Consumption Calculation:

For each coin motor:

- Operating voltage (V_{motor}) = 3.0 V
- Operating current (I_{motor}) = 90 mA = 0.090 A
- Power per motor (P_{motor}) = $V_{motor} \times I_{motor}$ = 3.0 V × 0.090 A = 0.27 W

For 18 motors at 100% duty cycle:

- Total power draw (P_{total}) = 18 × P_{motor} = 18 × 0.27 W = 4.86 W

Battery Capacity:

- Battery capacity (C) = 4,000 mAh
- Battery voltage ($V_{battery}$) = 4.8 V
- Energy storage capacity (E) = C × $V_{battery}$ = 4,000 mAh × 4.8 V = 19.2 Wh

Battery Life:

- Battery life (t) = E / P_{total} = 19.2 Wh / 4.86 W = **3.95 hours**

This calculation represents a worst-case scenario with all 18 motors operating at 100% duty cycle continuously. The actual battery life during typical use is expected to be significantly longer, as users typically: (1) Activate only selected motor groups (not all 18 motors), (2) Use duty cycles below 100% (commonly 25-75%), and (3) Turn the device off during periods when stimulation is not needed. For example, operating 9 motors at 50% duty cycle would extend battery life to approximately 7.9 hours, exceeding our target specification.

Battery Life Optimization Strategies

To address the battery life limitation in future iterations, we propose the following optimization strategies:

1. Pulse-width modulation (PWM) optimization: Implementing more efficient PWM control algorithms to reduce average power consumption [32] .

2. Low-power microcontroller: Replacing the Arduino Uno with a microcontroller designed for battery-powered applications (e.g., Arduino Nano Every, STM32L series).

3. Selective motor activation: Software features to encourage users to activate only necessary motor groups.

4. Higher capacity battery: Upgrading to 6,000-8,000 mAh batteries while maintaining weight <1 kg.

5. Sleep mode: Implementing automatic sleep mode during periods of inactivity.

<u>Noise Level</u>

A low noise level should be maintained to minimize public disruption and protect user privacy. We quantified the noise using an online decibel meter running on a laptop near the device, using the laptop's microphone as input. We established a baseline noise level by letting the decibel meter run with the motors off. Then, we turned the device on at 1 Hz and 50% duty cycle and took the maximum difference between the new measurement and the baseline value. We made two measurements: one with the motors uncovered, and one with pressure being applied to the motors (which better mimics how the device will perform during use). The maximum noise level when uncovered was 10 dB, and the maximum noise level covered was 5 dB. They both met our goal of less than 20 dB, which is equivalent to the noise level of someone whispering from 5 feet away.

<u>Surface Temperature</u>

A noticeable difference in temperature occurs when the coin motors run continuously. To ensure the motors do not reach an unsafe temperature, we used an infrared camera to track the temperature of one coin motor running at 100% duty cycle over 5 minutes. A photo was taken of the motor every 30 seconds (**Fig. 9**). The coin motor did not exceed 30°C, which is less than the target maximum temperature of 43°C (IEC 60601-1-11:2015) [33,34].

COMPARISON WITH EXISTING SENSORY FEEDBACK DEVICES

To contextualize our design, we compared the vibrotactile vest with existing commercial and research sensory feedback devices (**Table 3**). Our design offers unique features including open-source accessibility, customizable vibrotactile frequency control, and Bluetooth connectivity, while maintaining comparable weight and pressure specifications.

Device	Type	Weight	Adjustability	Mechanism	Control Interface	Cost	Open Source
Current Prototype	Vibrotactile + Compression	750 g	Frequency (1-100 Hz), duty cycle (0-100%), location	18 coin motors	Bluetooth smartphone app	~$150	Yes
Snug Vest [20]	Compression only	>324 g	Pressure levels	Deep pressure via inflation	Manual pump	~$250-400	No

Squease Vest [35]	Compression only	<250 g	Pressure levels	Deep pressure via inflation	Manual pump	~$300-500	No
Deep Touch Pressure Vest [36]	Compression only	400-600 g	Pressure levels	Compression via shape memory alloy springs	Heat via applied electrical current	Research prototype	No
Weighted vests [25]	Weight + compression	1-3 kg	Weight amount	Static pressure	N/A	~$50-150	N/A
Deep pressure vest prototype [30]	Pneumatic compression	Not reported	Pressure levels	Inflatable chambers	Electronic control	Research prototype	No
Vibrotactile torso stimulation [37]	Vibrotactile only	1-1.7 kg	Intensity levels, patterns, location	Vibration actuators	Computer control	$600	No

Table 3. Comparative analysis of sensory feedback vests. The current vibrotactile vest prototype is compared with existing commercial and research devices across key parameters.

Key Advantages of Current Design

Our design offers several key advantages over existing sensory feedback devices. Unlike compression-only devices, our vest provides adjustable frequency vibrotactile input ranging from 1 to 100 Hz, allowing users to identify optimal stimulation parameters for their individual needs. The device employs a dual mechanism that combines the benefits of compression therapy and vibrotactile stimulation, potentially leveraging complementary therapeutic effects [30,31] . Additionally, the open-source nature of our design means that all design files, source code, and assembly instructions are freely available, enabling other researchers and makers to replicate and modify the device to suit their specific requirements. The vest operates discretely, producing noise levels below 5 dB when covered and designed to be worn under clothing without detection. Finally, Bluetooth connectivity enables real-time adjustability, allowing users to make immediate parameter changes through the smartphone application without removing the device.

Limitations Compared to Existing Devices

Despite these advantages, our prototype has several limitations compared to existing devices. The current worst-case battery life of 3.95 hours is shorter than some commercial alternatives, though practical use with typical settings is expected to exceed this estimate. The external electronics holster is larger than ideal, and future versions should integrate these components into the vest fabric for improved comfort and discretion. The current device is only amenable to surface cleaning, which may not be adequate for long-term use. Most significantly, unlike some commercial devices that have undergone efficacy studies, our prototype has not yet been tested in clinical settings, and therapeutic claims remain hypothetical pending formal validation.

PILOT TESTING AND VALIDATION PLANS

Current Validation Status

This manuscript reports comprehensive technical characterization of the vibrotactile vest prototype, including: engineering specifications (weight, temperature, noise, pressure), signal fidelity (frequency and duty cycle accuracy), and battery performance. However, human usability and efficacy testing has not yet been conducted. The device's therapeutic potential remains hypothetical pending clinical validation.

Preliminary Informal Feedback

During development, we obtained informal feedback from consultation with an Autism Speaks Ambassador and Autism Society of Texas board member (see **Acknowledgments**) [38] . He emphasized the importance of user autonomy and voluntary use, expressing that any assistive device should remain entirely under the control of the individual using it. He also indicated a strong preference for a discrete design that could be worn under clothing to avoid unwanted attention or stigma. The importance of individual customization was highlighted, recognizing that sensory preferences vary widely among users. Additionally, he raised concerns about the potential for coercive use of such devices, which we have addressed through explicit ethical guidelines emphasizing informed consent, voluntary participation, and the user's right to remove the device at any time. This stakeholder engagement informed our design principles but does not constitute formal validation.

Recommended Validation Studies

We recommend a phased validation approach consisting of three sequential studies designed to establish safety, usability, and efficacy.

In Phase 1, usability and comfort testing will be conducted with 10-15 healthy volunteers over a 6-month period. This initial study aims to assess comfort during extended wear periods of 1-4 hours, evaluate the intuitiveness of the smartphone user interface, identify preferred vibration parameters, and document any adverse effects such as skin irritation or discomfort. Data will be collected through structured feedback questionnaires, visual analog scales for comfort ratings, and free-response interviews.

Phase 2 will expand testing to 20-30 neurodivergent individuals in a proof-of-concept study over 12-18 months. The primary objectives are to assess feasibility and acceptability in the target population and to obtain preliminary efficacy signals, including self-reported stress and anxiety changes, changes in focus and attention, and changes in stereotyped movement frequency. Feasibility and acceptability measures will include safety, thermal and tactile comfort, and hygiene issues with prolonged use. We will also identify individual parameter preferences to inform future device optimization. This phase will employ a single-arm, within-subject design using standardized assessments such as the State-Trait Anxiety Inventory and Visual Analog Scales, supplemented by behavioral observation and semi-structured interviews. Ethics approval from the institutional review board will be required prior to participant enrollment.

Phase 3 will be a randomized controlled efficacy trial comparing three conditions: the active vibrotactile vest, a sham vest providing compression only without vibration, and standard care. Outcome measures will be aligned with hypothesized mechanisms regarding the therapeutic benefits of rhythmic sensory input [6] and the results of the Phase 2 trial.

DISCUSSION

We describe the design and creation of a wearable vest that discreetly provides rhythmic vibrotactile stimulation to the body as an alternative or supplement to engaging in stereotyped movements [39]. The prototype showed accurate frequency and duty cycle control with low error and met most engineering specifications, except for battery life, which fell short of our 5-hour target. However, this worst-case calculation assumes continuous operation of all 18 motors at 100% duty cycle, and practical battery life during typical use patterns is expected to exceed our target.

Our vest design is part of a growing literature on wearable vibrotactile torso stimulation [37]. Prior work has explored the potential benefits of vibrotactile stimulation in multiple populations [40] including people with autism spectrum disorder [22] major depressive disorder [41], fibromyalgia [42], after trauma [43], in mild cognitive impairment and dementia [44], and ADHD [32]. In the general population there is growing demand for discreet and portable tools to increase focus and decrease stress [45–48]. To our knowledge, the prototype reported here is the first open-source design for a wearable vibrotactile vest. This work addresses a gap in assistive technology for people who rely on stereotyped movements for self-regulation. Fidgeting and stimming serve important roles in sensory regulation, maintenance of focus, and stress reduction [39,49]. However, they can be physically harmful in some cases or socially stigmatizing. Our approach represents a wearable system that aims to provide the sensory benefits of these movements without requiring overt motor activity.

Many people with autism have sensory hyper- and hyposensitivities to the degree that differences in sensory processing is a diagnostic criterion for autism spectrum disorder [50]. Our vest provides vibrations at low frequencies (<60 Hz), which typically stimulate a sensation referred to as “flutter” via Meissner’s corpuscles. The vest can also provide stimulation from 60-100 Hz, which induces a “vibratory hum” sensation, mediated by Pacinian corpuscles [51]. Peripheral sensory organs [52,53] and brainstem nuclei [54] are increasingly being investigated for their role in the pathophysiology of autism; thus the perceived sensation of the vibrations may be different than expected for people with autism. Indeed, because of individual differences in the peripheral and central nervous systems, the vest and the vibrotactile stimuli (and heat generated by the motors) may be interpreted as pleasing or aversive to different individuals.

We have identified several limitations and areas for improvement. One major limitation is the wiring, which requires a bundle of 11 wires from the holster to the vest, making it bumpy and uncomfortable. The device has no external port for charging, so the user must remove the batteries and charge them manually. The holster is larger than ideal, which may make the vest more difficult to handle and wear. The device could be made more comfortable and less complex by fabricating a custom flexible printed circuit board and using surface-mounted components. Serial or I2C communication would further reduce the number of wires. User experience could be improved by making the vest detachable from the holster and integrating the charging module, and by adding preset options for frequency, duty cycle, and motor selection. Additionally, temperature from the motors could be aversive when used over extended periods in hot ambient temperatures.

Most critically, this manuscript reports technical characterization only, and human usability and efficacy testing have not yet been conducted. The device's therapeutic potential remains hypothetical pending clinical validation through the phased approach outlined above. Translation to clinical use will also require compliance with relevant regulatory frameworks including IEC 60601-1-11 and ISO 14971 for medical electrical equipment and FCC wireless communication standards (e.g. Federal Communications Commission (FCC) Part 15).

Future improvements may include encapsulating motors in padding to distribute vibratory force, dissipate heat, and improve comfort. Pockets for additional weights and a network of elastic webbing and velcro could provide adjustable deep pressure. A feature to synchronize vibration patterns with sound could be added for therapeutic benefit [55]. We also foresee future closed-loop versions coupled with EEG or other technologies to activate the device and adjust frequency and pressure according to physiological variables such as brain rhythms. This would be especially useful to achieve nonintuitive patterns or to help people who are not able to fine-tune the stimulation parameters due to challenges in motor control or intellectual disability.

We emphasize that this device must never be used to suppress natural autistic behaviors or as a tool of compliance. Stereotyped movements serve important self-regulatory functions [4,5,39] and should be respected as valid forms of communication and self-expression [28,29]. This device is intended as an option for individuals who choose to use it, not a replacement for or suppression of natural behavior. Use should always be voluntary, with the wearer maintaining full autonomy and control over the device.

CONCLUSIONS

This open-source vibrotactile vest represents a novel approach to providing rhythmic sensory input as a potential alternative or complement to stereotyped movements. The prototype demonstrates technical feasibility with precise frequency control, user-friendly smartphone interface, discrete operation, and safe thermal performance. While the device meets most engineering specifications, battery life requires optimization, and substantial work remains to validate therapeutic efficacy, improve ergonomics, and achieve regulatory compliance. Human usability and efficacy testing are needed to determine whether the device delivers meaningful benefits to users. We are committed to pursuing rigorous, ethically sound research in partnership with the autism and ADHD communities. By making this design openly available, we hope to accelerate innovation in assistive technology and contribute to expanding options for individuals who benefit from rhythmic sensory input—always in service of user autonomy, dignity, and well-being.

FIGURES

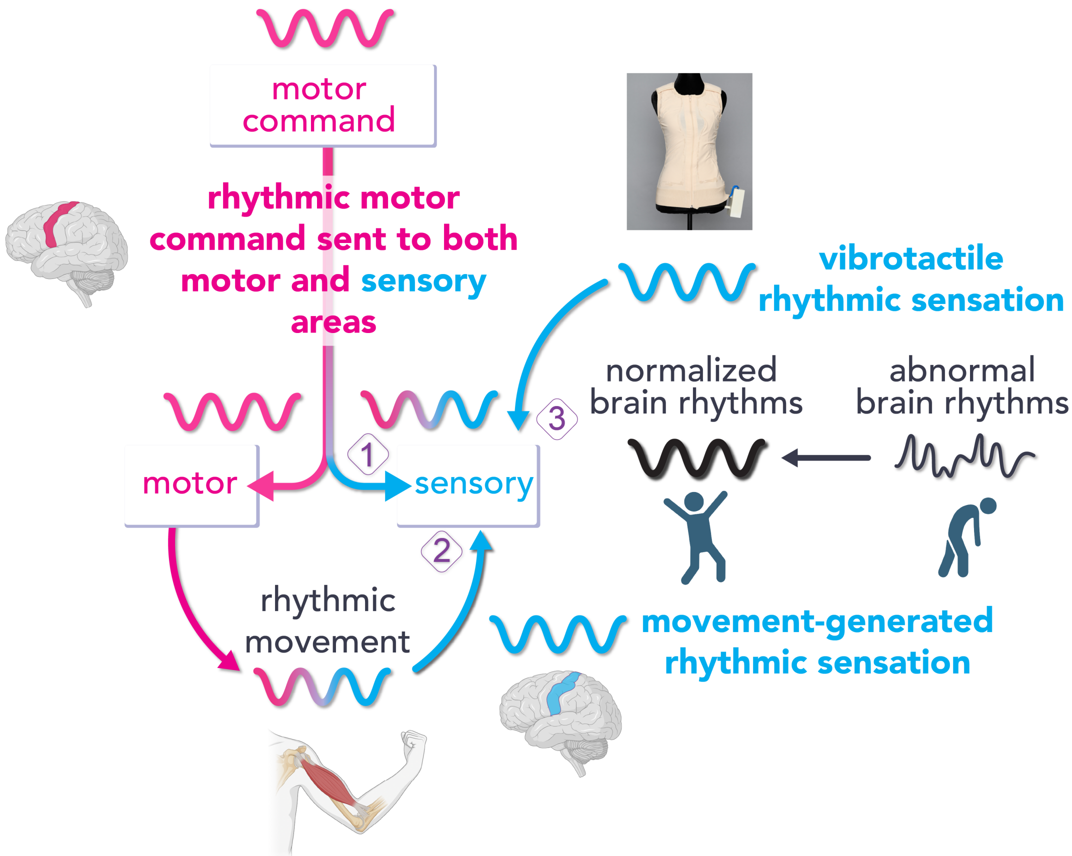


Figure 1. Hypothesized therapeutic benefit of rhythmic sensory inputs. Adapted from McCarty & Brumback 2021. We hypothesize that rhythmic sensory signals can regulate brain rhythms by 3 mechanisms: **1)** Efference copy allows the brain to interpret sensory signals as self-generated vs. non-self-generated. To signal that a movement is self-generated, motor command signals are simultaneously sent to both the motor system and the sensory system. The copy of the motor command provides the sensory system a “heads up” that the movement was generated from within. Thus, **efference copy** provides rhythmic input to the sensory system. **2)** The **rhythmic movements** produce rhythmic sensory feedback. **3)** An **external device** provides rhythmic sensory input. This model posits that rhythmic sensory input may serve as a therapeutic tool to normalize brain rhythms.

Figure 2. Vest prototype. **A.** Vest exterior. **B.** Vest interior. **C.** Batteries, Arduino Uno microcontroller, and Bluetooth module.

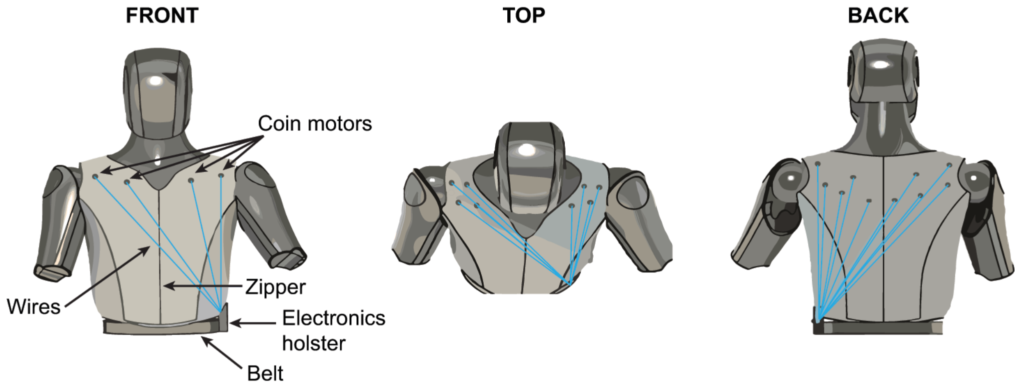


Figure 3. Front, top, and back view of the vibration vest design with coin motor placements (gray circles), wires (blue lines), belt, and holster containing the Arduino microcontroller, batteries, and Bluetooth module.

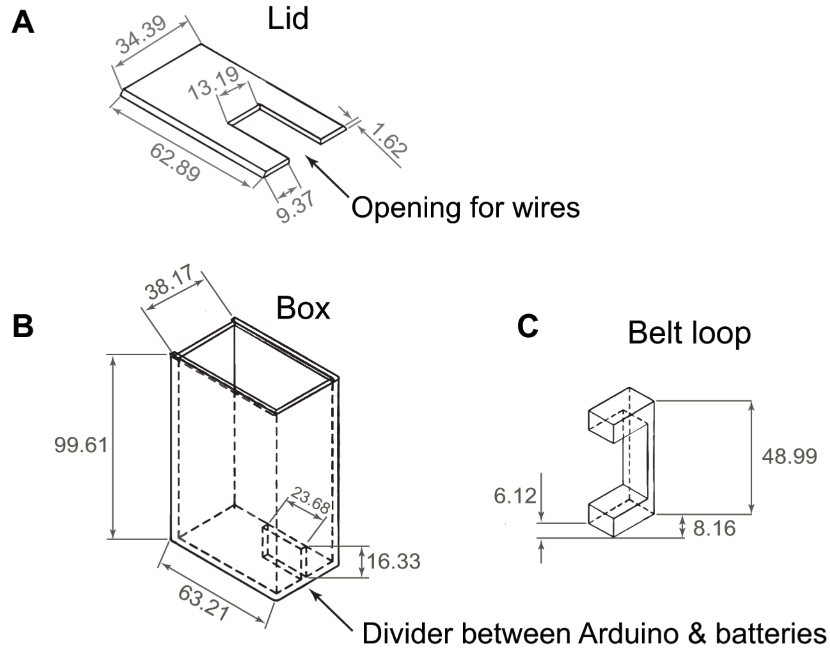


Figure 4. Computer-Aided Design (CAD) drawing of electronics holster components. (a) Box with divider between Arduino and batteries, (b) lid that slides onto box with a hole for wires and power switch, and (c) belt loop that is superglued onto the box to make the holster wearable.

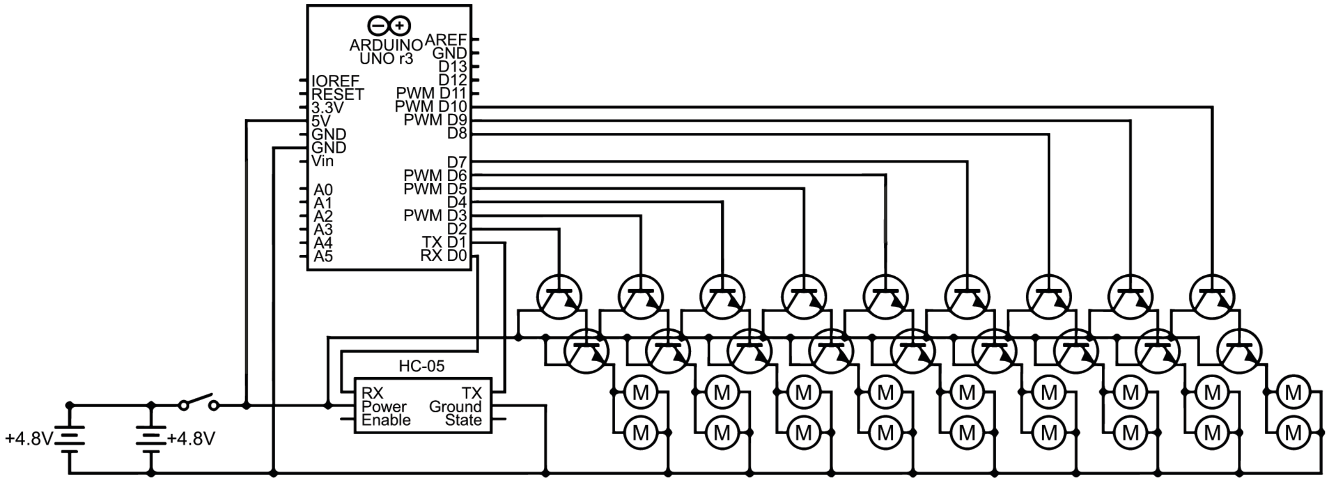


Figure 5. Circuit schematic of the vibrotactile vest control system.
An Arduino Uno r3 microcontroller controls 18 coin vibration motors (M; 8mm diameter, 3V DC) arranged in nine independently addressable pairs via Darlington-paired NPN transistors for current amplification. The Arduino outputs control signals through nine PWM-capable pins (D3, D5, D6, D9, D10, D11) and three digital pins (D4, D7, D8), enabling independent frequency (1-100 Hz) and duty cycle (0-100%) control for each motor pair. An HC-05 Bluetooth module connects to the Arduino's serial communication pins (TX/D1, RX/D0) for wireless control via smartphone application. Power is supplied by two series-connected nickel metal hydride batteries (+4.8V, 4,000 mAh combined capacity). Ground (GND) connections are shared across all components to complete the circuit.

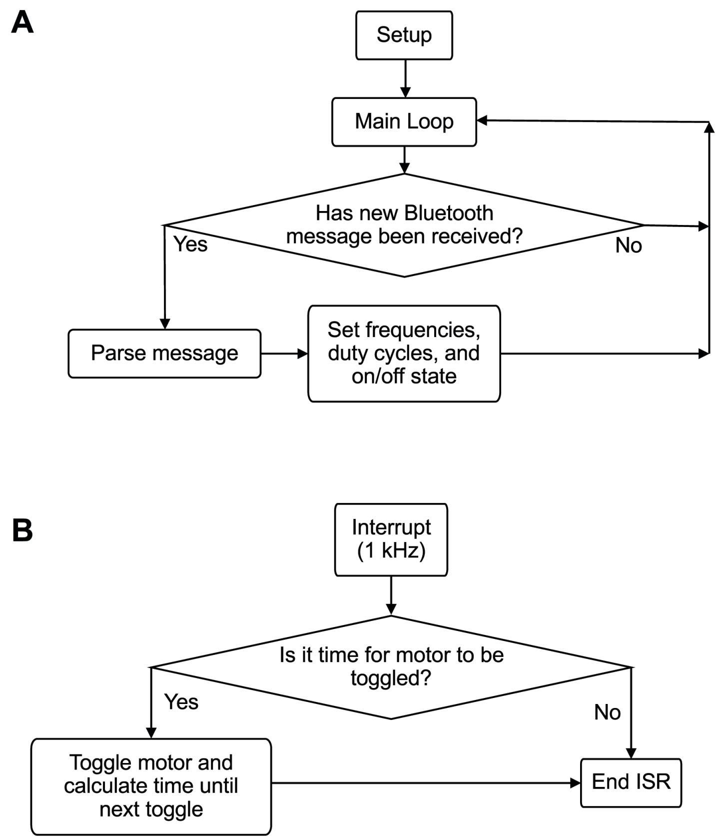


Figure 6. Arduino Software Flowchart. Control logic for the Arduino Uno microcontroller showing (top) the main program loop for receiving and parsing Bluetooth commands from the smartphone application, and (bottom) the 1 kHz interrupt service routine (ISR) for precise timing control of individual motor groups. Full code provided in Appendix A.

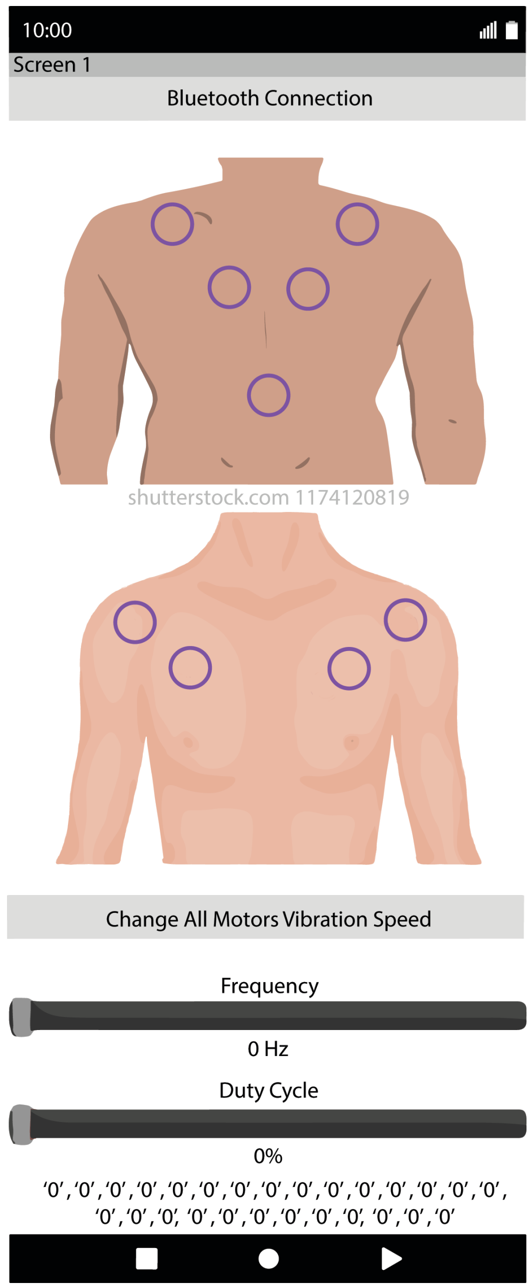


Figure 7. Android mobile application interface for controlling the vibrotactile vest via HC-05 Bluetooth module. The scrollable screen displays: (Top) Bluetooth connection button for selecting and connecting to the HC-05 module; (Middle) Interactive body diagrams showing motor group locations with clickable buttons for the upper chest (4 motors), shoulders (4 motors), lumbar region (2 motors), and trapezius/back area (8 motors), where users can individually select motor groups to turn on/off or click "Change All Motors Vibration Speed" to control all motors simultaneously; (Bottom) Two slider controls for adjusting vibration parameters: frequency slider (range: 1-100 Hz in 1 Hz intervals) and duty cycle slider (range: 0-100% in 1% intervals), with real-time numerical labels displaying current values below each slider. An additional label above the frequency slider indicates which motor region's attributes are currently being modified. The application was developed using MIT App Inventor and transmits user input changes to the Arduino microcontroller in real time via Bluetooth to allow users to quickly determine their preferred stimulation settings. Full application code is provided in Appendix B.

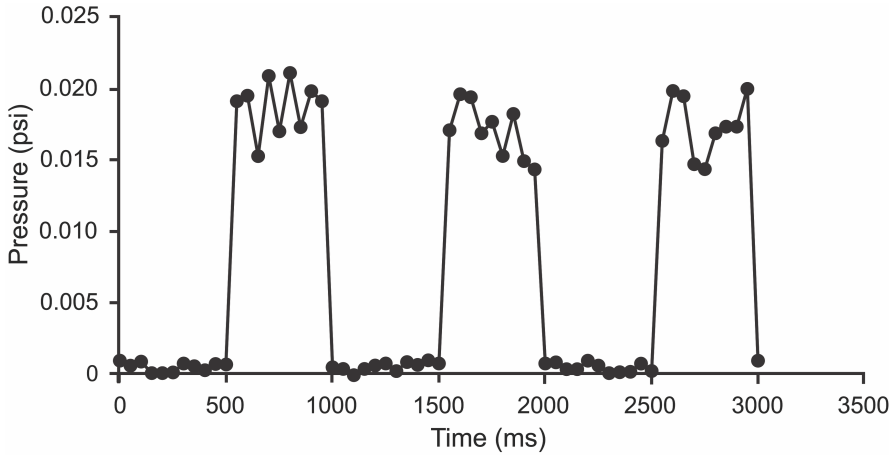


Figure 8. Pressure testing for one coin motor vibrating at 1 Hz frequency and 50% duty cycle. Pressures were 0.015 - 0.020 pounds per square inch (psi), or approximately 103 – 138 Pascal (Pa), meeting our requirement of at least 100 Pa.

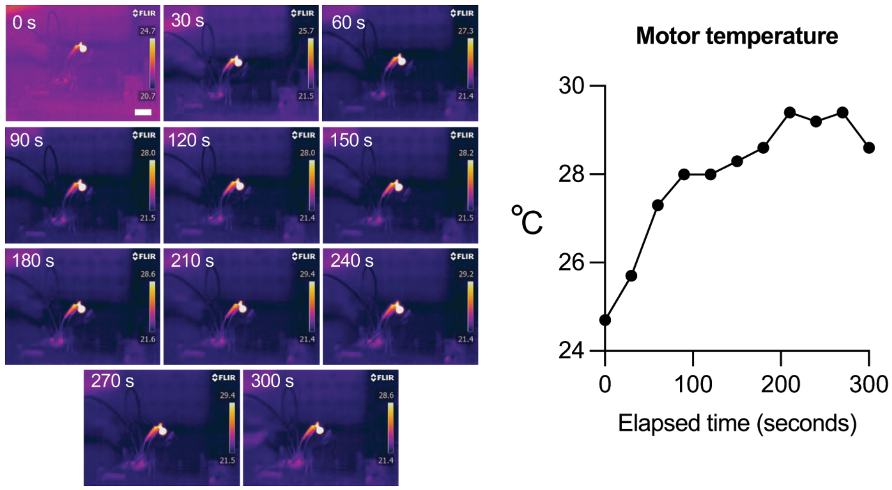


Figure 9. Temperature testing. Infrared thermal images of one coin motor running at 100% duty cycle. Photos were taken every 30 seconds over 5 minutes using an infrared camera (FLIR 620). Temperature ranged from 24.7°C in the first 30 seconds to a peak of 29.4°C. The maximum temperature remained below the safety threshold of 43°C for prolonged skin contact established by IEC 60601-1-11 for home healthcare medical devices (ISO, 2015). Scale bar = 20 mm.

SUPPLEMENTARY MATERIALS

All source code (Arduino, smartphone application, MATLAB, FSR testing) and detailed appendices are provided in the Supplementary Materials document and are also openly available in our online repository at https://github.com/BrumbackLab/VibratingVest.

Supplementary materials include:

- Appendix A: Arduino microcontroller code
- Appendix B: Smartphone application code
- Appendix C: MATLAB frequency estimate code
- Appendix D: Pressure sensor (FSR) code

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Supplemental Materials

An Open-Source Vibrotactile Vest Design for Personalized Rhythmic Sensory Input

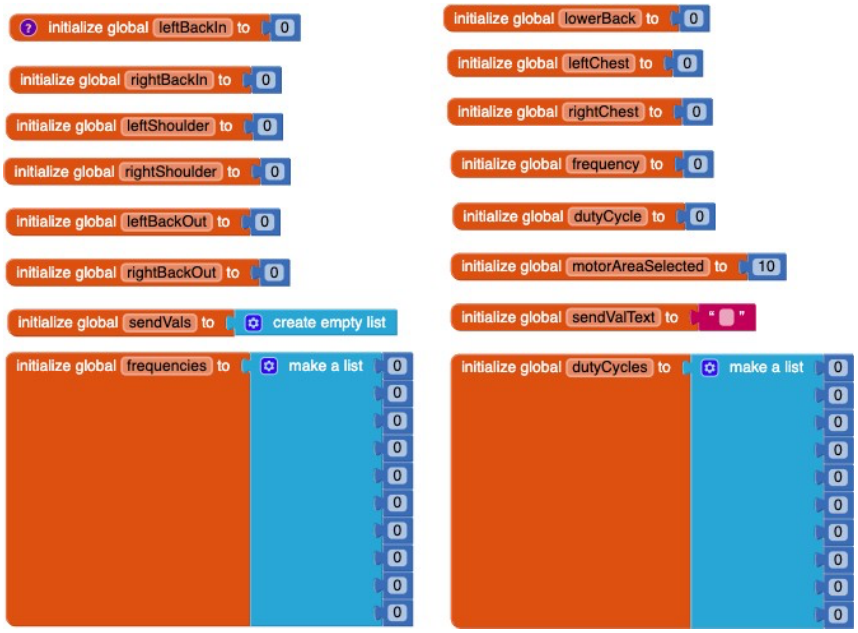
Gabriela Franco, Peter Lin, Emily Liu, Selim Uzgoren, Abhinav Vetcha, Jonathan T. Pierce, and Audrey C. Brumback

Appendix A. Arduino code

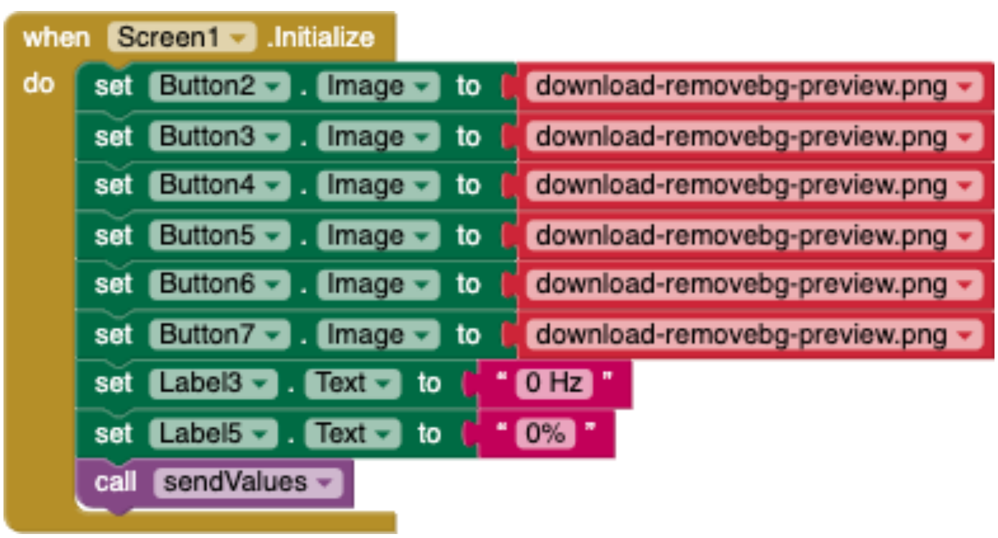
```
#define numRegions 2

#define minFreq 1
#define maxFreq 100
#define freqInc 1

#define minDuty 0
#define maxDuty 100
#define dutyInc 5

// Rotary encoder pin order #define CLK 0
#define DT 1
#define SW 2

// Pins for each motor region
int regionPin[numRegions] = {2, 4};

// Pins for each rotary encoder module (CLK, DT, SW) int rotaryPin[numRegions][3] = {{3, 5, 6}, {9, 10, 11}};

// CLK states for each rotary encoder int CLKState[numRegions];

// SW states for each rotary encoder int SWState[numRegions];

// Mode of reach rotary encoder (true = frequency, false = duty cycle) bool rotaryState[numRegions] = {true,
true};

// Initial settings for each motor region float freq[numRegions] = {1, 1};
int dutyCycle[numRegions] = {50, 50}; long timeLeft[numRegions];

// ******************************************************************************
// setup()
// Initializes pin modes and starting values
// ******************************************************************************

void setup() {
for (int i = 0; i < numRegions; i++) { pinMode(regionPin[i], OUTPUT);

pinMode(rotaryPin[i][CLK], INPUT); pinMode(rotaryPin[i][DT], INPUT); pinMode(rotaryPin[i][SW],
INPUT_PULLUP);

CLKState[i] = digitalRead(rotaryPin[i][CLK]); SWState[i] = digitalRead(rotaryPin[i][SW]);

timeLeft[i] = 10 * dutyCycle[i] / freq[i];
}

Serial.begin(9600); setupTimer1(1000);
}

// ******************************************************************************
// loop()
// Toggles motors on and off at a variable frequency and duty cycle
// ******************************************************************************

void loop() {
// Process rotary encoders and check if time to toggle motors for (int i = 0; i < numRegions; i++) {
processRotary(i);
}
```

```
}

// ****************************************************************************
// processRotary()
// Reads rotary encoder and adjusts frequency or duty cycle accordingly
// Input: region ID
// ****************************************************************************

void processRotary(int region) {

int CLKval = digitalRead(rotaryPin[region][CLK]); int DTval = digitalRead(rotaryPin[region][DT]); int SWval
= digitalRead(rotaryPin[region][SW]);

// If last and current state of CLK are different, then pulse occurred if (rotaryState[region]) {
// Frequency mode
if (CLKval != CLKState[region] && CLKState[region] == 1) { if (DTval == CLKval && freq[region] > minFreq)
freq[region] -= freqInc;
else if (freq[region] < maxFreq) freq[region] += freqInc;
}
} else {
// Duty cycle mode
if (CLKval != CLKState[region] && CLKState[region] == 1) { if (DTval == CLKval && dutyCycle[region] >
minDuty)
dutyCycle[region] -= dutyInc;
else if (dutyCycle[region] < maxDuty) dutyCycle[region] += dutyInc;
}
}

CLKState[region] = CLKval;

// Button has been released
if (SWState[region] == LOW && SWval == HIGH) rotaryState[region] = !rotaryState[region];

SWState[region] = SWval;

}

// ****************************************************************************
// ISR(TIMER1_COMPA_vect)
// Toggles motors on and off
// ****************************************************************************

ISR(TIMER1_COMPA_vect) {
for (int i = 0; i < numRegions; i++) {

if (dutyCycle[i] == 0) { digitalWrite(regionPin[i], LOW); continue;
} else if (dutyCycle[i] == 100) { digitalWrite(regionPin[i], HIGH); continue;
}

timeLeft[i]--;
if (timeLeft[i] <= 0) {
if (digitalRead(regionPin[i])) {
timeLeft[i] = 10 * (100-dutyCycle[i]) / freq[i]; digitalWrite(regionPin[i], LOW);
} else {
timeLeft[i] = 10 * dutyCycle[i] / freq[i]; digitalWrite(regionPin[i], HIGH);
}
}

}
}
```

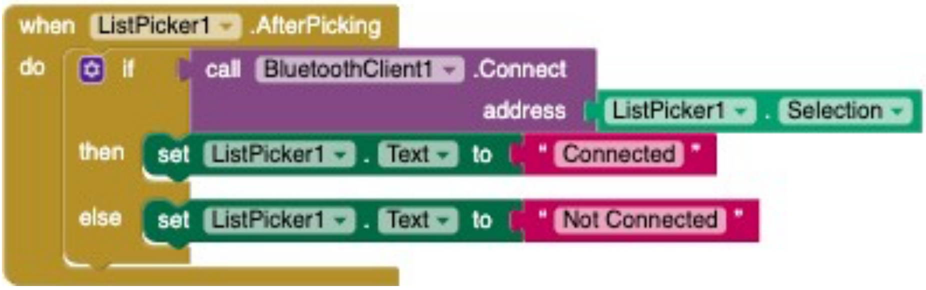
Appendix B. Smartphone Application Code



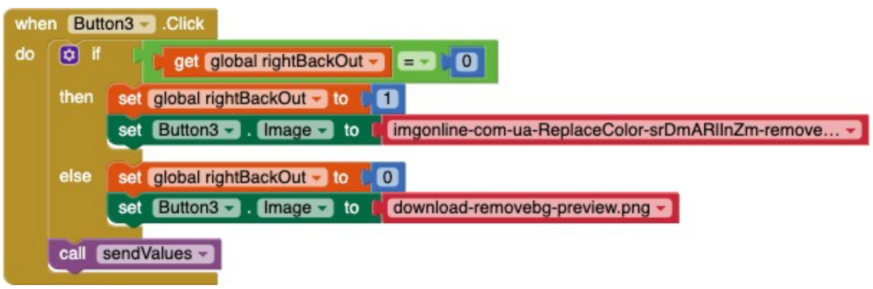
Initializes all variables needed for the user interface code.



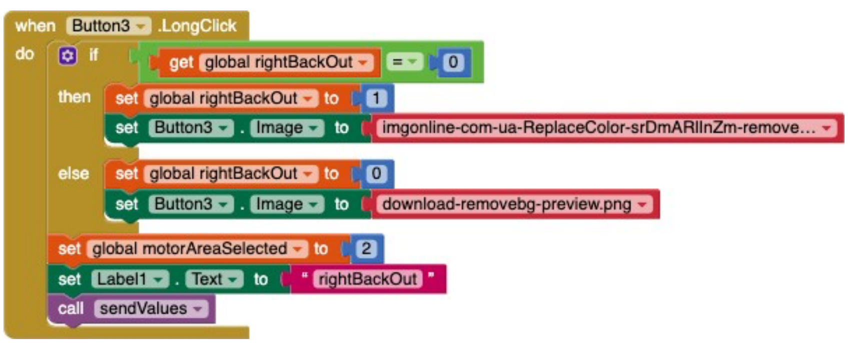
Initializes all buttons to show as not selected and initializes starting labels for frequency and duty cycle sliders.



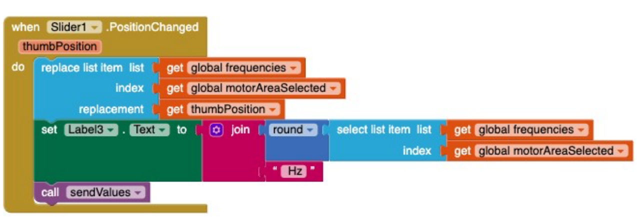
Allows user to set up Bluetooth connection to HC-05 Bluetooth module from phone application.

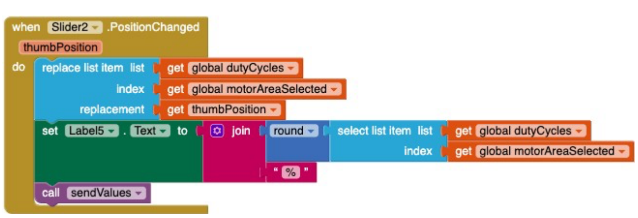


Allows user to click certain buttons to turn on certain motor areas, repeated for all motor area buttons.

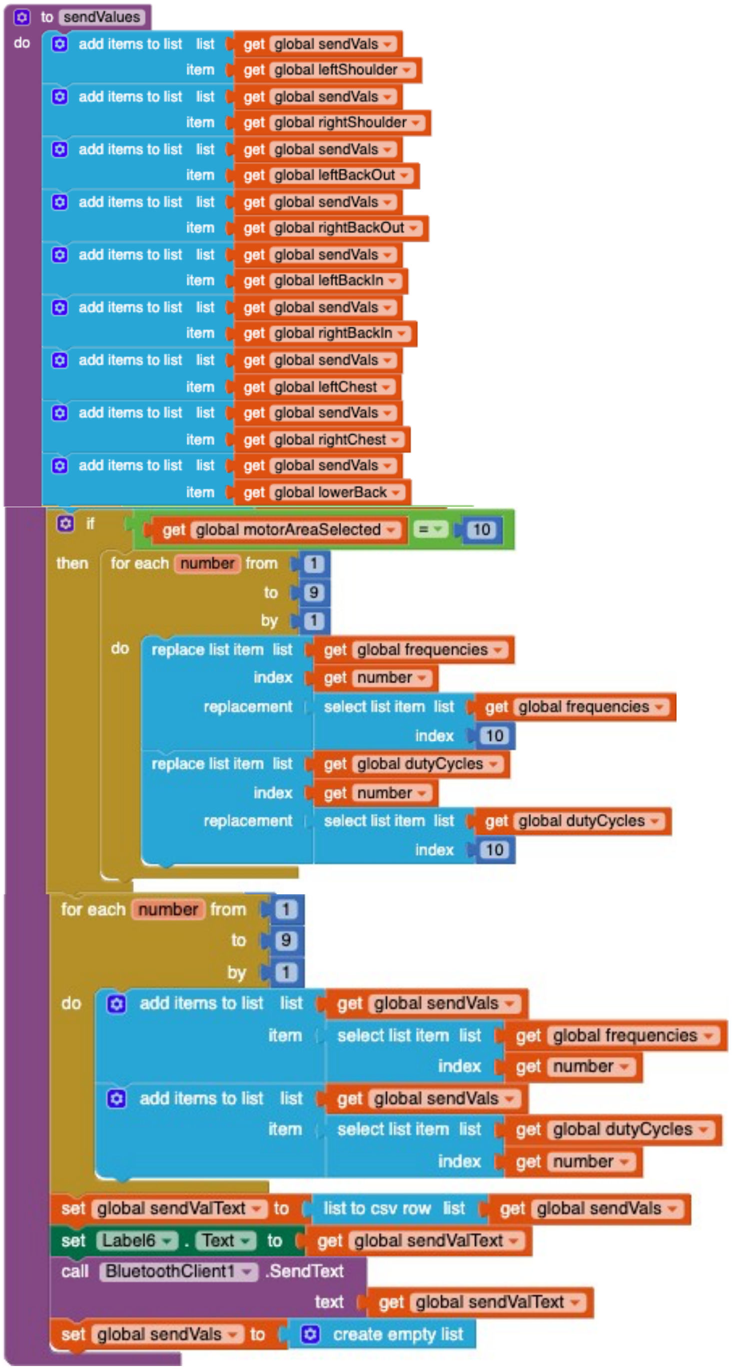


Allows user to click and hold to select a motor area and then change the frequency and duty cycle for only that motor area, repeated for all motor area buttons.





Allows user to modify frequency and duty cycle using sliders of a specific motor area or all motors based on what was previously selected.



sendValues function is called every time a user modifies a parameter on the application and sends motor areas selected, frequencies, and duty cycles to the Arduino as a string, which are then parsed by Arduino code.

Appendix C. MATLAB Frequency Estimate Code

```
%% Calculate Frequency of Signal

file = "Frequency and Duty Cycle Testing v3"; sheet = "freq50";

% Read data from Excel sheet data = xlsread(file, sheet); time = data(:,1);
val = data(:,2);

% Create new variables for padding out time2 = 0:time(end);
val2 = zeros(1, length(time2));

% Fill in gaps from original data (emulate sampling at 1 kHz) ind = 1;

for i = 1:length(time2)
if time(ind) ~= time2(i) val2(i) = val2(i-1);
else
val2(i) = val(ind); ind = ind + 1;
end
end

% Perform fast fourier transform L = length(time2);
y = fft(val2);

p2 = abs(y/L); p1 = p2(1:L/2+1);
p1(2:end-1) = 2*p1(2:end-1);

f = 1000*(0:(L/2))/L;
plot(f, p1);

% Output frequency estimate [~, index] = max(p1(1:end)); f(index)
```

Appendix D. Pressure Sensor (FSR) Code

```
// Pressure Sensor (FSR) Code
// One end of FSR connected to +3.3V, other end connected to A0 with pull-down resistor

const int analogInPin = A0;
//const int analogOutPin = 9; const int R1 = 10050;
double R2;
int sensorValue = 0; int outputValue = 0; double voltage = 0; double pressure;

void setup() { Serial.begin(9600);
}

void loop() {
sensorValue = analogRead(analogInPin); outputValue = map(sensorValue, 0, 1023, 0, 255);
//analogWrite(analogOutPin, 255); voltage = 3.3*outputValue/255;

R2 = R1 * ((3.3/voltage) - 1.0);
//Serial.println(R2);

pressure = 23949*pow(R2, -1.31); Serial.println(pressure); delay(100);
}
```

Editor's Checklist

This checklist is specific for the Journal of Medical Devices, in addition to the general author's checklist for all ASME journals. The completed checklist must be submitted as Supporting Information.

General

- ☒ The main text must be organized with the following main headings/sections: Abstract, Introduction, Methods, Results, Discussion (this may be combined together with the Results as Results and Discussion), and Conclusions. Methods may not be needed for paper types (e.g., review) that do not include original data.
- ☒ If a manuscript is focused on developing a new method, most of the info on the new method must be included in the Results section.
- ☒ Subheadings are strongly encouraged under Methods, Results, and Discussion sections.
- ☒ All acronyms must be spelled out at their first appearance except in the manuscript title.
- ☒ All figures (and their panels for multi-panel figure), tables, and equations must be numbered in the same order as their appearance in the test. For example, Fig. 1B must be mentioned after Fig. 1A in the text.
- ☒ Cite papers published in this journal when appropriate
- ☒ No more than 10 figures in the main manuscript, although there is no limit on the number of figures in the Supplementary Materials
- ☐ No more than 2 Tables (except for review papers) in the main manuscript, although there is no limit on the number of tables in the Supplementary Materials.
- ☒ Ensure smooth transitions from sentence to sentence and from paragraph to paragraph.

Title (no more than ~25 words)

- ☐ The title is essentially a shorter version of the Abstract and focused on the most novel/unique/significant. methods and results reported in this work for its aimed applications, in terms of addressing the remaining challenges in the field.
- ☐ Acronyms may be used in title, but must be spelled out in the Abstract at first appearance.

Abstract (no more than ~250 words)

- ☒ The Abstract must be in one paragraph with no subheading, and is a concise summary of the whole paper including Introduction, Methods, Results, Discussion, and Conclusions.
- ☒ No citing of references in the Abstract.
- ☒ The abstract must include information on:
  - ☒ What the major biomedical problem/disease relevant to this work is
  - ☒ What has been done and what challenge(s) remain that are to be addressed in this work
  - ☒ What the unique/new methods are for addressing the challenge(s) in this work
  - ☒ How well the challenge(s) can be addressed in this work (i.e., important results)
  - ☒ What the broad significance of this study is in one last sentence.
- ☒ Keywords (5-10) that are not in the title must be given.

Introduction (no more than ~1000 words)

- ☒ This is essentially the expanded version of the info for Abstract (except the last bullet point on broad significance) mentioned above.
- ☒ References must be cited to support any important statement regarding work published in the literature.
- ☒ No subheadings in this section
- ☒ Introduction must have more than one paragraph.

Methods

- ☒ All methods must be described in detail to the extent that they can be repeated by others, to ensure repeatability.
- ☒ Subheadings must be used in this section to guide the reader.
- ☒ This work does not involve human subjects (or procuring human tissue from human subjects).
- N/A ☐ This work involves human subjects (or procuring human tissue from human subjects):
  - N/A ☐ A statement must be given to inform that the human study was approved/exempted by a specific ethics committee in your institution.
  - N/A ☐ In the above statement, the full name of the ethics committee must be given followed by an acronym in parentheses (e.g., Institutional Review Board (IRB), etc.).
  - N/A ☐ The approval/exempt # of the human study specific for this work must be provided.
- ☒ This work does not involve animal study.
- N/A ☐ This work involves animal study:
  - ☐ A statement must be given to inform that the animal study was approved/exempted by a specific ethics committee in your institution.

N/A ☐ In the above statement, the full name of the ethics committee must be given followed by an acronym in parentheses (e.g., Institutional Animal Care and Use Committee (IACUC), etc.).

N/A ☐ The approval/exempt # of the animal study specific for this work must be provided.

N/A ☐ A last section with the subheading "Statistical Analysis" must be included to summarize the methods used for statistical analysis and the criteria used for being statistically significant, better, higher, etc., to ensure scientific rigor.

☒ In rare cases, if no section on Statistical Analysis is included, please justify briefly: *No statistical analyses were performed.*

Results

☒ Subheadings must be used to guide the reader.

☒ To ensure scientific rigor, all quantitative results must be presented either as plots with error bars (standard deviation (SD)) in figures (preferred) or as mean +/- SD in tables. Standard error of mean (SEM) may be used. It must be made clear in the manuscript whether SD or SEM is used.

☒ The number (n) of independent experiments/animals/human subjects/tissue samples, etc., must be given in the figure or table caption, to ensure scientific rigor.

☒ Figures

- ☒ A scale bar must be given for either each image or each group of images with the same scale bar in each figure.
- ☒ The scale-bar size must be either labeled clearly above each scale bar in the figure or described clearly in the figure caption.
- ☒ The number of figures should match approximately with the number of subheadings in this section.
- ☒ Plots, images, or sketches from the same experimental study or supporting the same point (e.g., given as subheadings in this section) must be consolidated into a multi-panel figure.
- ☒ In captions of multi-panel figures, a brief overall summary of the figure in approximately one line must be given before describing the different panels in the figure. This overall summary can be similar to the subheading if the number of figures follow the number of subheadings in this section.
- ☒ All symbols/labels in a figure must be explained in either the figure or its caption.
- ☒ No figure (either in part or as a whole) of this paper is published elsewhere already.
- ☒ Any component that is published already elsewhere must have permission, which must be made clear per the party who owns the copyright. The evidence showing permission was obtained must be submitted as Supporting Information.

☒ All figures (e.g., Fig. 1), all panels in multi-panel figures (e.g., Fig. 2g), and all tables (e.g., Table 1) must be cited in order.

☒ All claims of significant difference must be supported by statistical analysis, to ensure scientific rigor.

Discussion (may be combined with the Results section)

☒ Minimize repeating things already stated in the Results section

☒ References must be cited to support any important statement regarding work published in the literature.

☒ Subheadings may be used but are not required.

Conclusions

☒ This section must summarize the major methods and results and conclude with a sentence on the broad significance of the methods and results.

☒ Must have no citing of references.

☒ Must be in one paragraph with no subheading

Conflict of Interest

☒ A conflict of interest (COI) statement must be included. Refer to [this webpage] for determining potential COI.

☒ If no COI, please state: The authors disclose no conflicts of interest or competing financial interests.

N/A ☐ If there is any COI, please disclose the relevant conflict(s) in detail.

References

☒ For references with multiple authors, the first 11 authors must be listed before "et al." can be used.

Table of contents (TOC) graphic

☒ An original (i.e., made by the authors), color (if possible), and simple but informative TOC graphic must be provided.

☒ The TOC graphic must be a structure, graph, drawing, photograph, scheme, or combination of the aforementioned with minimal text.

☒ The TOC graphic can help capture the reader's attention and give readers a quick visual impression of the essence of the manuscript, when displayed with the paper title and abstract on the journal website.

☒ The TOC graphic must be submitted as an image file.