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Building and operating a vibrotactile feedback device for seated balance assessment and training

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Alisha DSouza, Ph.D.
Senior Review Editor
Journal of Visualized Experiments (JoVE)

October 12, 2018

Dear Dr. DSouza,

Please find enclosed our revised methodological manuscript (JoVE58611R2) titled: "Building and Operating a Vibrotactile Feedback Device for Seated Balance Assessment and Training", authored by AD Williams and AH Vette. In this manuscript, we report on the development, assembly, and operation of a modular and portable device for the rehabilitation, assessment, and training of dynamic sitting posture using vibrotactile feedback.

We have now revised the manuscript according to the constructive editorial and reviewer comments, which have helped us to significantly improve our work. We are confident that the revised version of the manuscript addresses all comments and that the content of the manuscript is now acceptable for publication in *JoVE*. I would like to confirm that both authors were fully involved in the study and the preparation of the manuscript, and that the proposed material has not been and will not be submitted for publication elsewhere.

Should you have any questions or comments pertaining to the submitted manuscript, please do not hesitate to contact me in person.

Sincerely,

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TITLE:
A Vibrotactile Feedback Device for Seated Balance Assessment and Training

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KEYWORDS:
Balance, biofeedback, device, postural stability, sitting, training

SHORT ABSTRACT:
A sitting platform has been developed and assembled that passively destabilizes sitting posture in humans. During the user's stabilizing task, an inertial measurement unit records the device's motion, and vibrating elements deliver performance-based feedback to the seat. The portable, versatile device may be used in rehabilitation, assessment, and training paradigms.

LONG ABSTRACT:
Postural perturbations, motion tracking, and sensory feedback are modern techniques used to challenge, assess, and train upright sitting, respectively. The goal of the developed protocol is to construct and operate a sitting platform that can be passively destabilized while an inertial measurement unit quantifies its motion and vibrating elements deliver tactile feedback to the user. Interchangeable seat attachments alter the stability level of the device to safely challenge sitting balance. A built-in microcontroller allows fine-tuning of the feedback parameters to augment sensory function. Posturographic measures, typical of balance assessment protocols, summarize the motion signals acquired during timed balance trials. No dynamic sitting protocol to date provides variable challenge, quantification, and sensory feedback free of laboratory constraints. Our results demonstrate that non-disabled users of the device exhibit significant changes in posturographic measures when balance difficulty is altered or vibrational feedback provided. The portable, versatile device has potential applications in rehabilitation (following skeletal, muscular, or neurological injury), training (for sports or spatial awareness), entertainment (*via* virtual or augmented reality), and research (of sitting-related disorders).

INTRODUCTION:

Upright sitting is a prerequisite for other human sensorimotor functions, including skilled movements (*e.g.*, typing) and perturbed balance tasks (*e.g.*, riding on a train). To rehabilitate and improve sitting and related functions, modern balance training techniques are used: unstable surfaces perturb sitting[1,2] and motion tracking quantifies balance proficiency[3,4]. Balance training outcomes improve when vibration is delivered to the body using patterns that match performance[5]. Such sensory feedback is evidently effective as a rehabilitation and training method; yet, current sensory feedback methods are geared towards standing balance and require laboratory-based equipment[6,7].

The purpose of the work presented here is to build a portable device that can be sat upon and passively destabilized to various degrees while built-in instruments record its position and deliver vibrational feedback to the sitting surface. This combination of tools integrates previous work on wobble chairs[2,4] and vibrational feedback[5–7], making the benefits of these tools more powerful and accessible. Also presented are a procedure to train upright sitting and an analysis of the quantitative outcomes, following the established literature on posturographic measures[8]. These methods are appropriate for studying the effects of sitting balance exercise with an unstable surface when combined with vibrational feedback. Anticipated applications include sports training, general improvement of motor coordination, assessment of balance proficiency, and rehabilitation following skeletal, muscular, or neurological injury.

PROTOCOL:

All methods described here have been approved by the Health Research Ethics Board of the University of Alberta.

1. Construction and Assembly of Structural Components

1.1. Use a computer numerical controlled (CNC) milling machine to construct a cylindrical chassis, lid, and base from polyethylene as shown in **Figure 1**. Apply grip tape or another suitable upholstery to the lid. Bolt the base to the chassis.

NOTE: The mill features for attachment of bolts and other parts are according to the drawing files and 3D solid model files provided (see **Supplementary Files 1** and **2**). All structural components have a corresponding solid model and drawing that are available for download and can be used to replicate the construction process.

1.2. Construct an attachment interface for interchangeable hemispherical bases: weld a base nut to a steel weld plate. Insert the base stud through the center of the chassis and bolt the base stud to the base, as shown in **Figure 1**.

1.3. Insert a rod through the center of the base and thread the rod into the base stud such that approximately 35 mm of the rod protrudes from the base. Use a milling machine to construct a cylindrical polyvinyl chloride sleeve that fits the protruding rod, as shown in **Figure 1**. Make the sleeve 37 mm long, with an outer diameter of 32 mm.

1.4. Weld steel flanges to each side of a steel hitch, as shown in **Figure 1**. Bolt the hitch to the front of the base.

1.5. Use a CNC turning machine to construct 5 identical cylinders from polyethylene, each with a height of 63 mm and a diameter of 152 mm. In the center of the top surface of each cylinder, cut a 32 mm hole to a depth of 38 mm so that it fits the cylindrical sleeve (*see Step 1.3. above*) with some interference.

1.6. On the bottom surface of each cylinder, use a CNC turning machine to cut a uniformly curved base with a unique radius of curvature for each of the 5 cylinders, maintaining the overall height of 63 mm, as shown in **Figure 2**.

NOTE: The radius of curvature and height of the base determine the stability of the device. The suggested radii of curvature for this height are between 110 mm (very unstable) and 250 mm (slightly unstable), as shown in **Table 1**.

1.7. Construct a leg support attachment as shown in **Figure 3**, by first welding a 70 mm steel hitch insert perpendicularly to one end of a 575 mm steel extrusion. At the other end, clamp a 300 mm cylindrical steel footrest to the extrusion. For detailed part dimensions, see **Supplementary File 1 (drawings)** and **Supplementary File 2 (3D solid models)**.

1.8. Use a bandsaw to cut a rectangular steel bar (29 mm by 100 mm) to a length of approximately 160 mm so that it weighs 3.6 kg. Insert the steel bar at the back of the chassis to counterbalance the leg support attachment, as shown in **Figure 1.**

1.9. Assemble the device as shown in **Figure 4**. Connect the leg support by inserting clevis pins through the hitch and hitch insert. Adjust the location of the clamp to the desired foot rest height. Insert the protruding rod into the desired curved base. Put on the lid.

2. Instrumenting the Device

2.1. Acquire a microcontroller (see the **Table of Materials**), an inertial measurement unit and eight vibrating tactors. Connect the inertial measurement unit and vibrating tactors to the microcontroller.

2.2. Program the microcontroller such that it reads antero-posterior (AP) and medio-lateral (ML) tilt angles from the inertial measurement unit and turns the vibrating tactors on or off based on the tilt angles. See **Supplementary File 3 (exemplary microcontroller script)** and Step 2.2.1.

NOTE: Inertial measurement units that utilize accelerometers and gyroscopes are prone to error. Perform a positional calibration of the sensors: rest the device on a level surface and use this position as a baseline for all following measurements. Use a motion capture system or similar approach to validate the tilt angle measurements and ensure that they are sufficiently accurate throughout the expected range of use (spatial and temporal). Ensure the vibrating tactors operate at a frequency of no more than 200 Hz, so as to induce a one-to-one response of sensory receptors in human skin or muscle[9].

2.2.1. Upload the microcontroller script that generates vibrotactile cues based on a feedback control signal that represents a weighted sum of AP (or ML) tilt angle and velocity.

NOTE: The computer activates three tactors closest to the left, right, front, or back of the surface when the control signal exceeds a threshold in that direction; or five tactors if an AP and ML threshold are surpassed simultaneously; none of the tactors are active when the control signal is below the threshold in both directions (*i.e.,* in the no-feedback zone).

2.3. Secure the inertial measurement unit in the center of the chassis. Arrange the vibrating tactors on a regular octagon with a radius of 10 cm, centered 8 cm anterior of the center of the chassis so that they will lie under the seat of an average-sized person[10]. A photograph of one potential arrangement is shown in **Figure 4**.

NOTE: If the vibrating tactors are not powerful enough to vibrate the user, improve the interface between tactor and skin by cutting holes into the lid and fixating the vibrators to rest flush with the surface. If the method used to secure the vibrators in place causes dampening of the vibration, consider using a two-part mounting enclosure with a loose-fit locating pin, as shown in **Figure 5**.

2.4. Connect the microcontroller to a laptop or desktop computer *via* a universal serial bus (USB) or other suitable communication method. Open the user interface, shown in **Figure 6**.

NOTE: Alternatively, connect the microcontroller to a battery or other power source. This improves the portability of the device, but precludes a user interface.

3. Exemplary Assessment and Training Protocol

3.1. Recruit consenting participants who are free of neurological or musculoskeletal disorders and acute or chronic back pain. Record each participant's age, weight, and height. Then, for each participant, carry out the following procedure.

3.2. Open the user interface (**Figure 6**). The compass graph shows the device's tilt angle plus half its tilt velocity in the AP direction (vertical axis) and ML direction (horizontal axis).

3.3. Prior to each balance trial, instruct the participant to don noise-cancelling headphones, fold his or her arms across the chest, maintain an upright posture as much as possible, and verbally cue the experimenter of being ready.

3.4. Perform twenty 30 second seated balance trials in series[11], taking breaks as warranted to avoid fatigue, stopping at any time if necessary.

3.4.1. Sequence the trials as follows (example only): randomly select one of two “base stability level/eye condition” combinations, hereafter called *balance conditions* (more difficult base and eyes open; or less difficult base and eyes closed)[12]. Perform four trials of the first balance condition to familiarize the participant with the task and to identify appropriate control signal thresholds for the vibrating tactors in the seat (*see Step 3.4.5 below*).

NOTE: It is more difficult to maintain balance on a base with a small radius of curvature than on a base with a large radius of curvature (**Table 1** shows the relative stability of all five interchangeable bases). Four trials have been found to be sufficient to achieve a stable performance of the balance task[2].

3.4.2. Randomly select three of the next six trials to be control trials: switch the vibrating tactors off for the duration of these trials. To turn the vibrational feedback on or off, toggle the **Feedback** slider to the desired setting in the user interface. Repeat this sequence of ten trials for the second balance condition.

3.4.3. Label the current difficulty and eye condition by selecting from the drop-down menus in the **Trial Parameters** section of the user interface. Click **Record** to start the trial.

NOTE: The participants’ safety is paramount. The experimenter should supervise all balance activities and be prepared to assist in the event of balance loss. Clear the area of any potential hazards and be aware of local emergency protocols.

3.4.4. For trials with eyes open, instruct the participant to focus on a fixed point straight ahead to help maintain balance. For trials with eyes closed, use a blindfold to ensure that the participant is completely deprived of visual feedback.

NOTE: For balance paradigms where the movement of the feet should be restricted, attach the foot support and insert the counterbalance beneath the lid.

3.4.5. An algorithm computes which AP and ML feedback thresholds to use and displays them in the **Q3** column of the user interface. After four familiarization trials, copy the values shown in the **Q3** column into the **Write** Column, and then click **Refresh** to update the feedback thresholds shown on the compass graph (pink) based on the fourth familiarization trial.

NOTE: The computed threshold values displayed in the **Q3** column of the interface are equal to the third quartile for each tilt direction (AP, ML) during the previous trial. This feedback scheme is based on the notion that balance function is improved when feedback is optimized for each individual[13,14], while providing too much feedback may detriment learning[15]. Once the two threshold values have been selected for a given individual, they can be kept constant for that individual to be able to assess improvements over time or with an intervention.

3.5. As the AP and ML tilt angles are automatically stored, in real-time, in a text file for analysis, analyze the AP and ML signals to characterize sitting performance for each of the experimental conditions.

3.5.1. In time domain, calculate the following posturographic measures from each time series[8]: root-mean-square (a measure of the variance of the motion) and the mean velocity (a measure of the average angular speed of the motion).

3.5.2. In frequency domain, calculate the following posturographic measures from each time series[8]: centroidal frequency (a measure of the motion's overall frequency) and frequency dispersion (a measure of the variance in the motion's frequency)[8].

3.6. Use a linear mixed model to estimate and characterize the effects of two fixed-effects factors, (1) the balance condition (stability level and eye condition combined) and (2) vibrotactile feedback, on each of the posturographic measures (dependent variables), considering the correlation of repeated measurements from each participant[16] (one random-effects factor).

3.6.1. Test for significance of the fixed effects by computing the ratio of the variance between the group means to the variance of the residuals, and comparing the result to an F-distribution.

REPRESENTATIVE RESULTS:

Table 2 shows, for each experimental condition, the posturographic measures derived from observations of the AP and ML support surface tilts, averaged over 144 balance trials performed by 12 participants (2 x 2 x 3 trials per participant).

Effect of Changing the Balance Condition: The base condition was chosen to be dependent on the eye condition (*i.e.,* when the eyes were closed, the base was more stable). Thus, the base and eye condition together were considered one independent variable (balance condition). Observations of AP tilt were significantly different between the two balance conditions for root-mean-square, centroidal frequency, and frequency dispersion (according to F-tests of the estimated change, $\alpha = 0.05$). The computed change in each of the measures (mean and standard deviation) is shown in **Figure 7** and **Figure 8**. Consistent with other reports, these posturographic measures can discriminate between balance tasks[4].

Effect of Changing the Feedback Condition: During trials when the vibrotactile feedback system was active, the centroidal frequency of AP tilt observations was significantly higher than during the control trials (according to F-tests of the estimated change, $\alpha = 0.05$). The computed change in each of the posturographic measures (mean and standard deviation) is shown in **Figure 9** and **Figure 10**. Consistent with other reports, this vibrotactile feedback protocol has a measurable effect on balance performance[17].

FIGURE AND TABLE LEGENDS:

Figure 1: Exploded view of the chassis assembly. Structural components include: (1) lid; (2) counterweight; (3) cylindrical chassis; (4) base stud; (5) hitch for attachment of leg support attachment (**Figure 3**); (6) base; and (7,8) rod, and sleeve for attachment of one of five interchangeable cylinders (**Figure 2**).

Figure 2: Side view of a curved base module. Each of the five modules has a total height of 63 mm and a unique radius of curvature, which modulates the difficulty of maintaining balance on the sitting surface.

Figure 3: Exploded view of the leg support attachment. The leg support, consisting of a hitch, clamp, and square finishing plug, is 600 mm long and can be removed during transportation of the device or to permit the user to swing the legs freely during balance exercise. For detailed part dimensions, see **Supplementary Files 1 (drawings)** and **2 (3D solid models)**.

Figure 4: **A vibrotactile feedback device for seated balance assessment and training.** (**A**) Exploded view of the device's attachments. The components shown here are: (1) the base, chassis, and lid; (2) the steel extrusion for footrest attachment; (3) two clevis pins to secure the footrest; (4) the footrest attachment of adjustable height; and (5) one of five curved base modules. These components can be separated to facilitate transportation or storage. For detailed part dimensions, see **Supplementary Files 1 (drawings)** and **2 (3D solid models)**. (**B**) Top view photograph of the device. The lid has been removed to reveal electronic instrumentation, including: an inertial measurement unit housed by a custom-printed enclosure (center); a microcontroller board with universal serial bus connection (left); eight electronic vibrators held in custom-printed enclosures (mid-region); and a steel bar (top) to counterbalance the footrest This figure has been modified from Williams *et al.*[18]. Republished with permission of ASME, from "Design and Evaluation of an Instrumented Wobble Board for Assessing and Training Dynamic Seated Balance" in the Journal of Biomechanical Engineering, AD Williams, QA Boser, AS Kumawat, K Agarwal, H Rouhani, AH Vette, vol. 140, April 2018; permission conveyed through Copyright Clearance Center, Inc.

Figure 5: Two-part mounting enclosure for vibrating tactors. A 4 mm hole in the tactor enclosure (top) fitted loosely on a 3 mm locating pin in the mounting platform (bottom) to minimize vibration dampening. For detailed part dimensions, see **Supplementary Files 1 (drawings)** and **2 (3D solid models)**.

Figure 6: User interface. This user interface allows users to select vibrotactile feedback thresholds and acquire data. The length and direction of the vector on the graph are proportional to the kinematics of the device. The rectangle reflects the AP and ML thresholds for feedback. This figure has been modified from Williams *et al.*[18]. Republished with permission of ASME, from "Design and Evaluation of an Instrumented Wobble Board for Assessing and Training Dynamic Seated Balance" in the Journal of Biomechanical Engineering, AD Williams, QA Boser, AS Kumawat, K Agarwal, H Rouhani, AH Vette, vol. 140, April 2018; permission conveyed through Copyright Clearance Center, Inc.

Figure 7: Results of task manipulation in time-domain. Change in time-domain posturographic measures when participants close their eyes and concurrently switch to a more stable base (mean and standard deviation; asterisk represents significant change according to F-test, $\alpha = 0.05$).

Figure 8: **Results of task manipulation in frequency domain.** Change in frequency-domain posturographic measures when participants close their eyes and concurrently switch to a more stable base (mean and standard deviation; asterisks represent significant change according to F-test, $\alpha = 0.05$).

Figure 9: Results of vibrotactile feedback in time-domain. Change in time-domain posturographic measures when participants are provided with performance-based vibrotactile feedback (mean and standard deviation; no changes were statistically significant according to F-test, $\alpha = 0.05$).

Figure 10: Results of vibrotactile feedback in frequency domain. Change in frequency-domain posturographic measures when participants are provided with performance-based vibrotactile feedback (mean and standard deviation; asterisk represents significant change according to F-test, $\alpha = 0.05$).

Table 1: **Geometrical properties of the interchangeable bases.** The total height of each base module is 63 mm; thus, a base with a smaller radius of curvature, when attached to the device, is less stable than a base with a larger radius of curvature.

Table 2: Results by balance and feedback conditions. Summary measures derived from AP and ML tilts during unstable sitting trials. Support surface stability plus eye condition as well as vibration level are the manipulated variables. Average measures were calculated across all participants.

DISCUSSION:

Methods for constructing a portable, instrumented, sitting device are presented. The device is portable and durable, building on previous studies of wobble chairs[2,4] and vibrational feedback[5–7] to make the benefits of these tools more powerful and accessible. Follow the assembly protocol in reverse to prepare the device for transportation or storage. The difficulty of the balance task can be modulated by attaching bases with different curvatures. The selection of task difficulty is critical; users should be destabilized to facilitate active training without risking injury.

Real-time observation and adjustment of the built-in instruments relies on serial communication between the microcontroller and the user interface; dysfunction of the device requires both software and hardware troubleshooting. Ensure that all hardware connections are secure. Monitor the serial output of the microcontroller for unexpected bytes. Probe the user interface program for errors. If a problem persists, consult an experienced mechatronics designer.

Balance proficiency is characterized by posturographic measures derived from kinematic observations of the sitting surface. Alternatively, observe the center of pressure exerted on a force plate, which correlates with the surface tilt angle[2], but requires additional equipment. Posturographic measures have varying reliability between sessions[2] and varying sensitivity to balance improvement or disorder[19]. The root-mean-square, mean velocity, centroidal frequency, and frequency dispersion are common posturographic measures that were observed to be linearly independent of each other. Consider modifying the signal analysis protocol to address particular assessment objectives.

The device delivers vibrotactile stimuli to the seat in accordance with balance task performance. The optimal configuration of haptic feedback control is the subject of continuous study and a critical step in this protocol, as certain feedback strategies may impair motor learning[20]. Existing vibrotactile feedback methods are proven to improve standing balance function and many other motor tasks[6,7]. Seat-embedded tactors make the vibrotactile feedback technique accessible for seated balance paradigms. Future applications may include sports training, spatial orientation training, virtual or augmented reality gaming, assessment of balance proficiency, research of balance disorders, and rehabilitation following skeletal, muscular, or neurological injury.

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DISCLOSURES:
The authors have nothing to disclose.

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Figure 1

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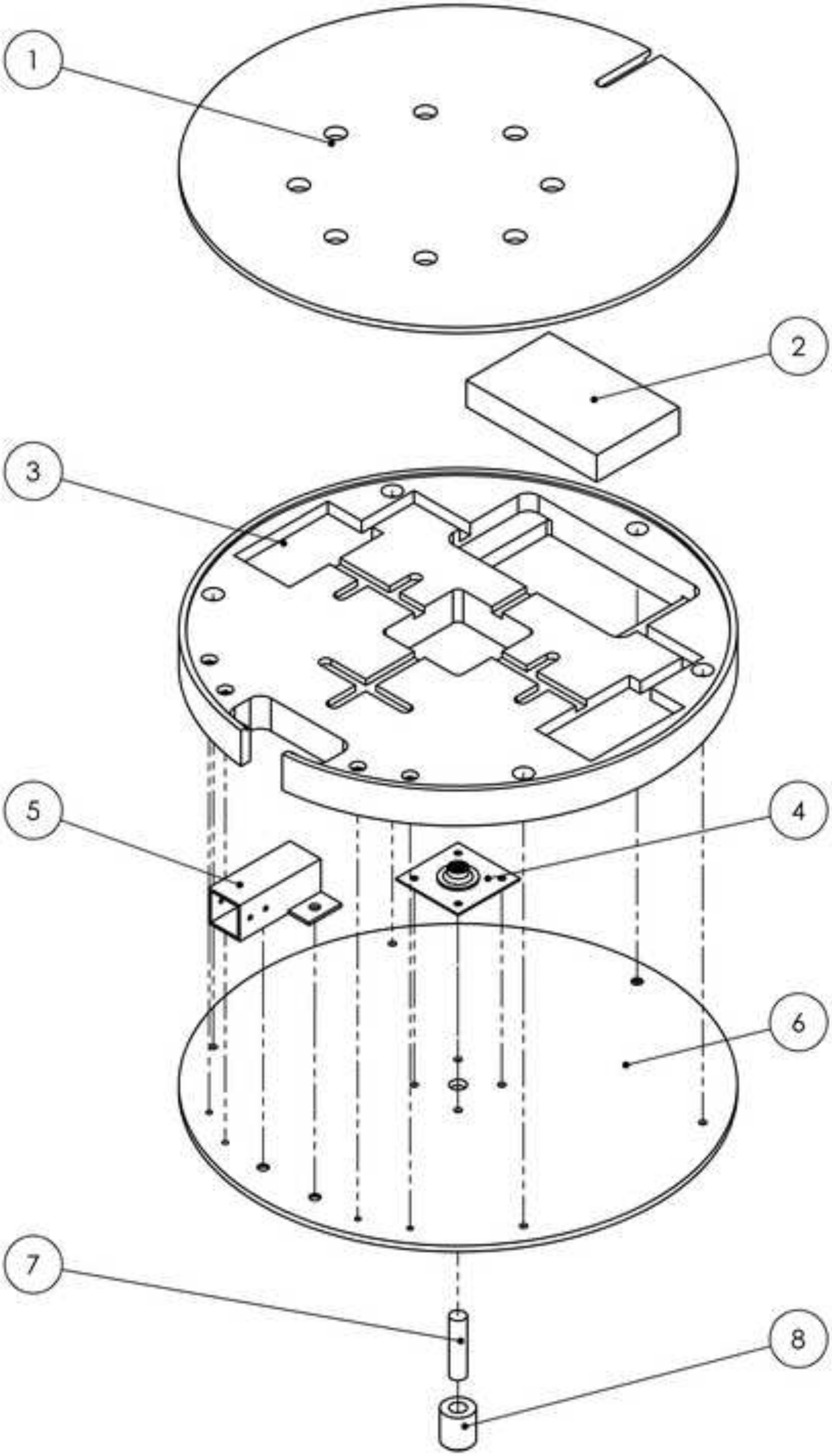

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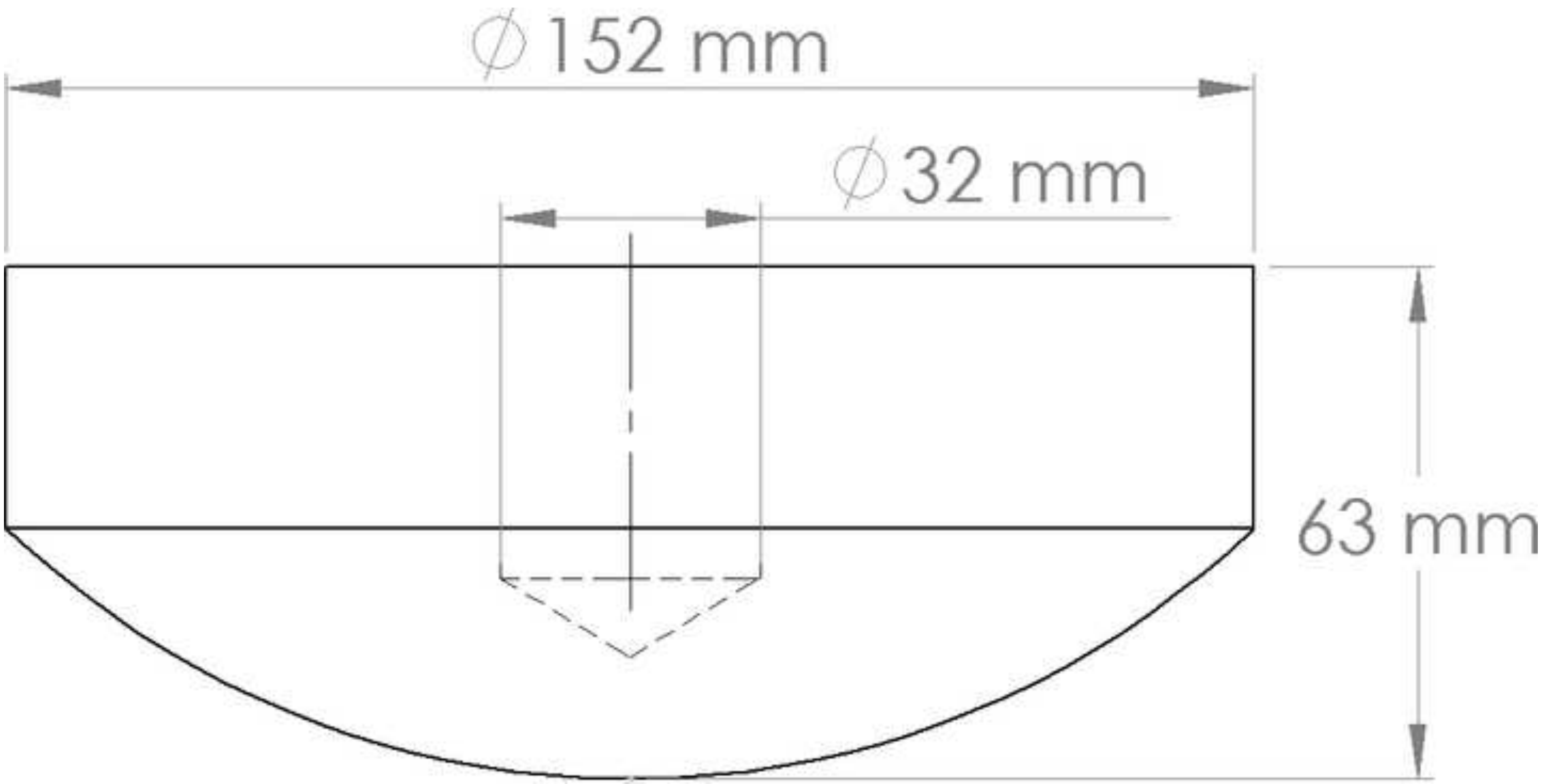

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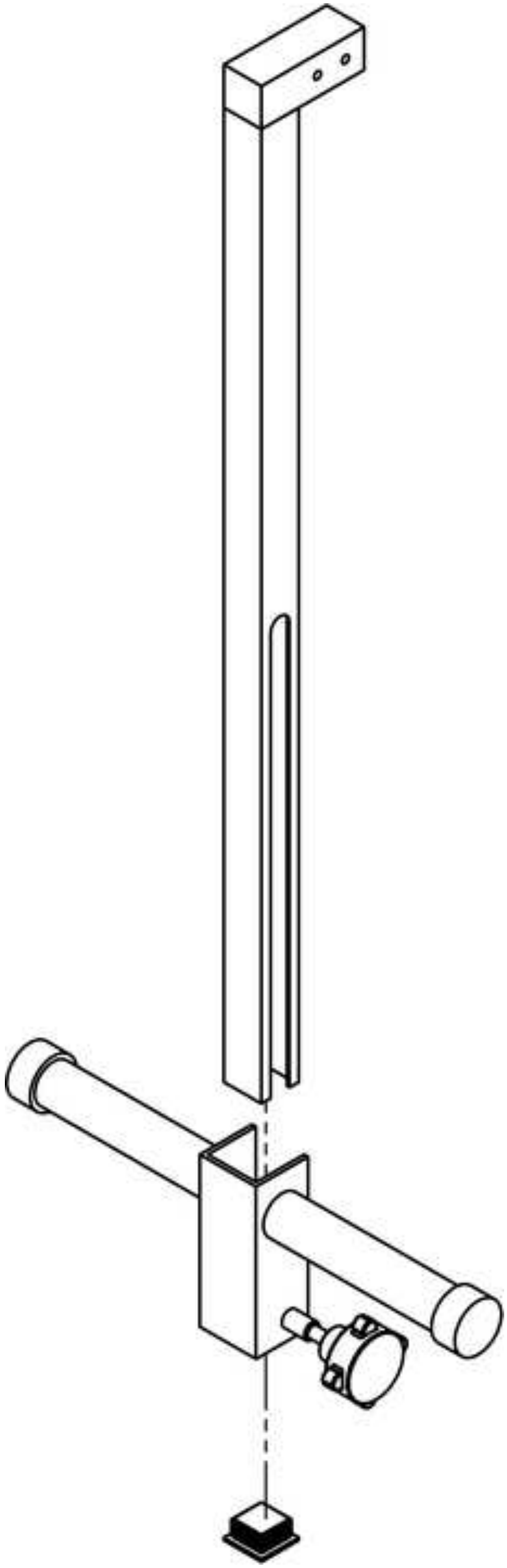

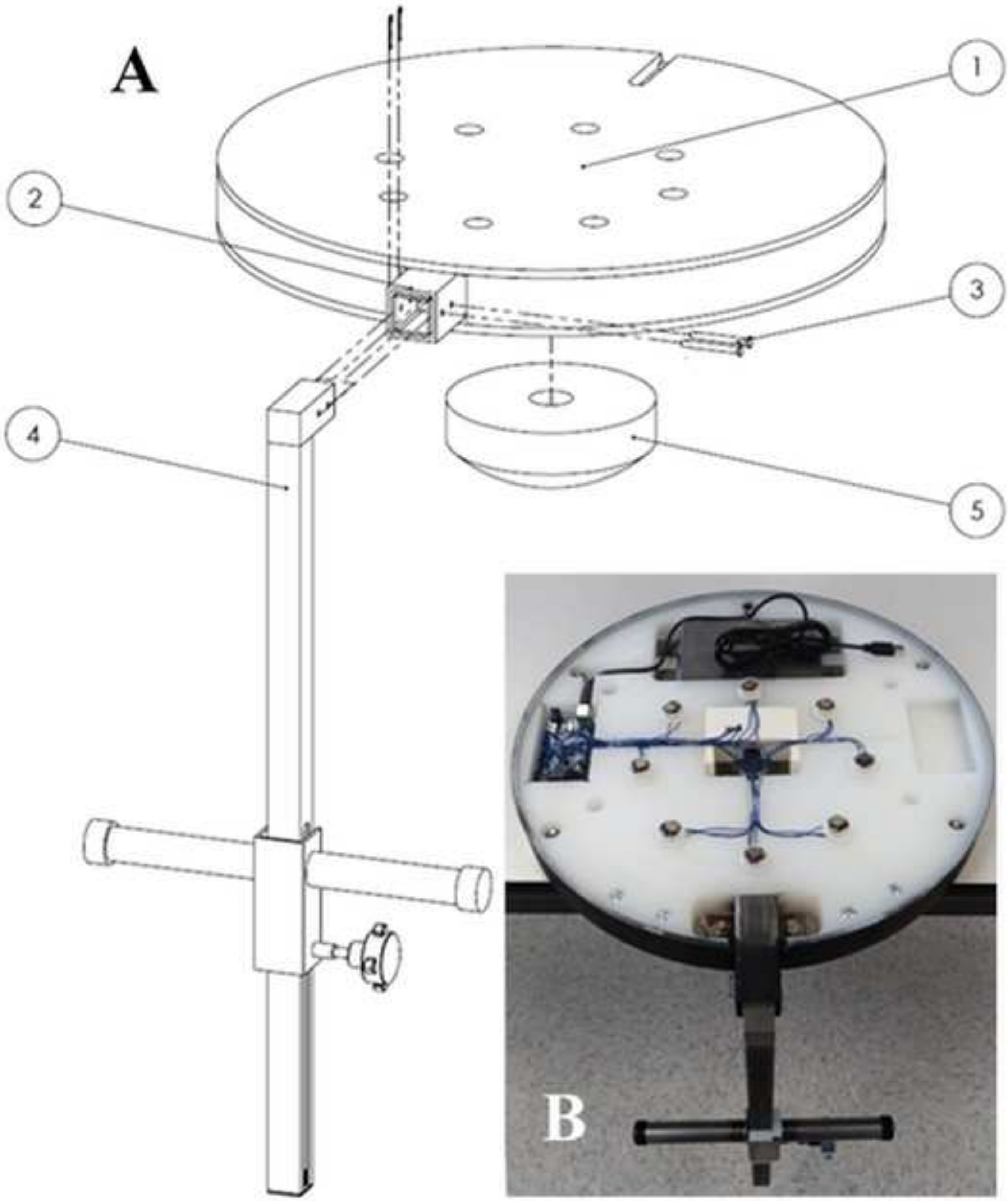
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Figure 5

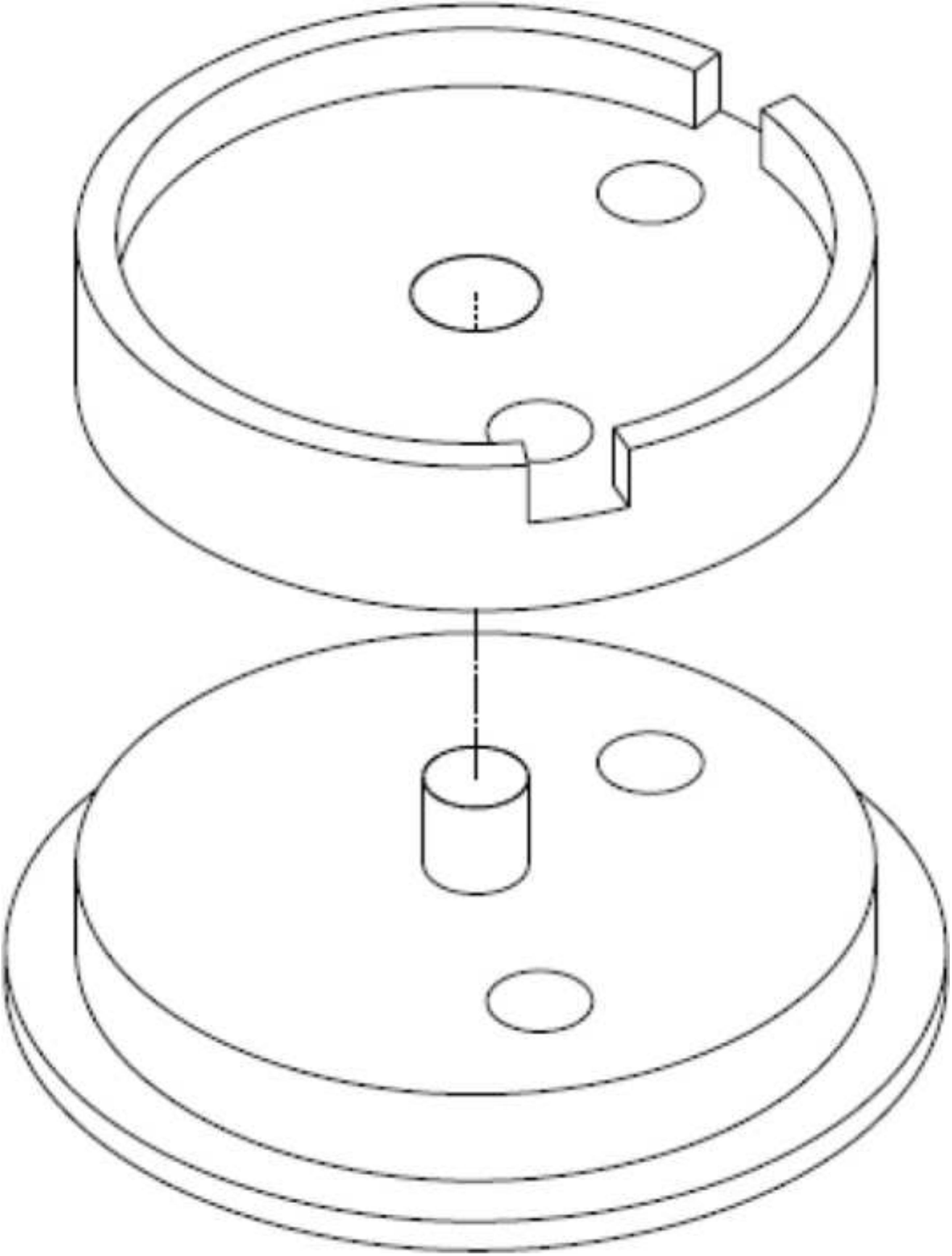

Figure 6

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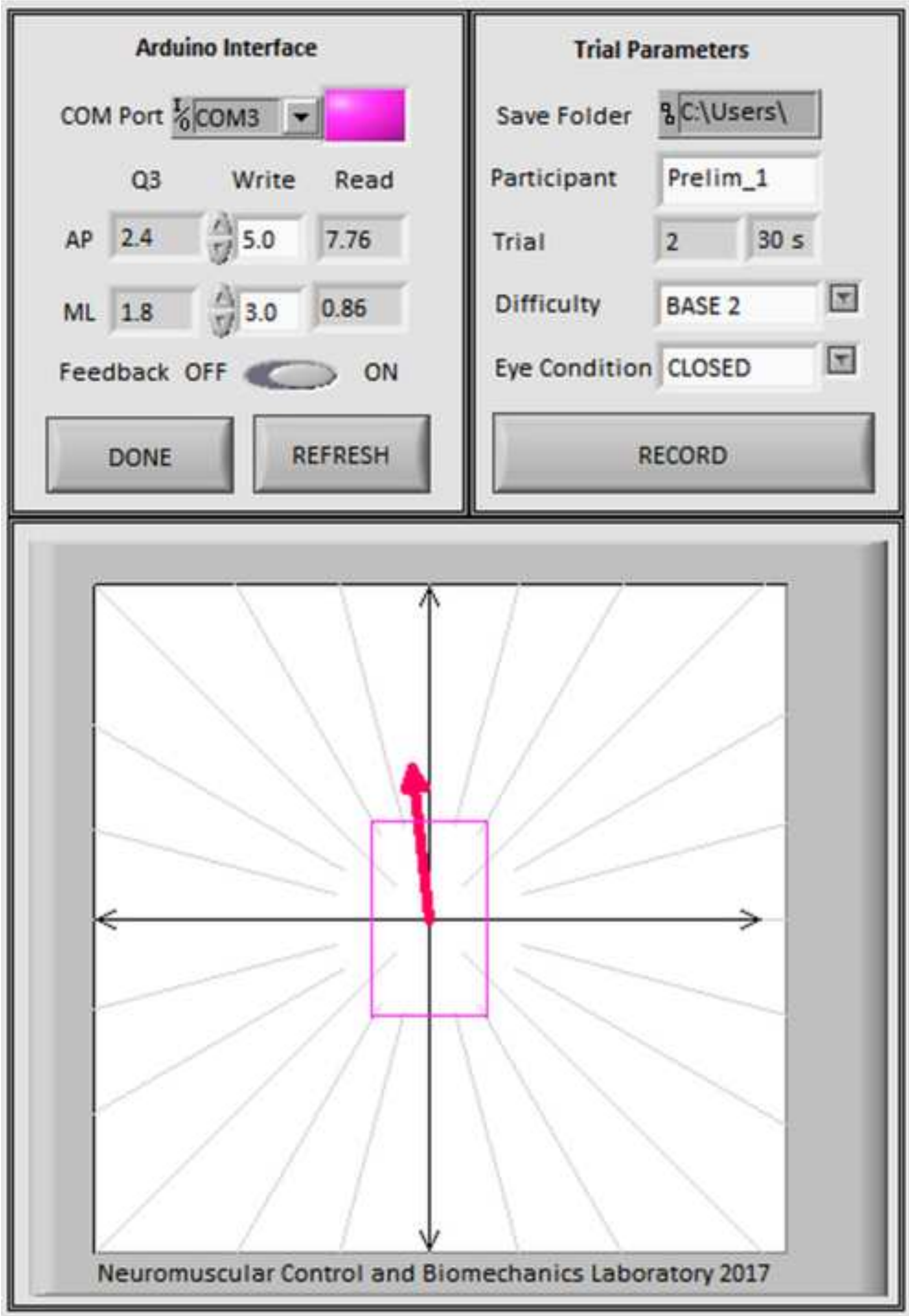

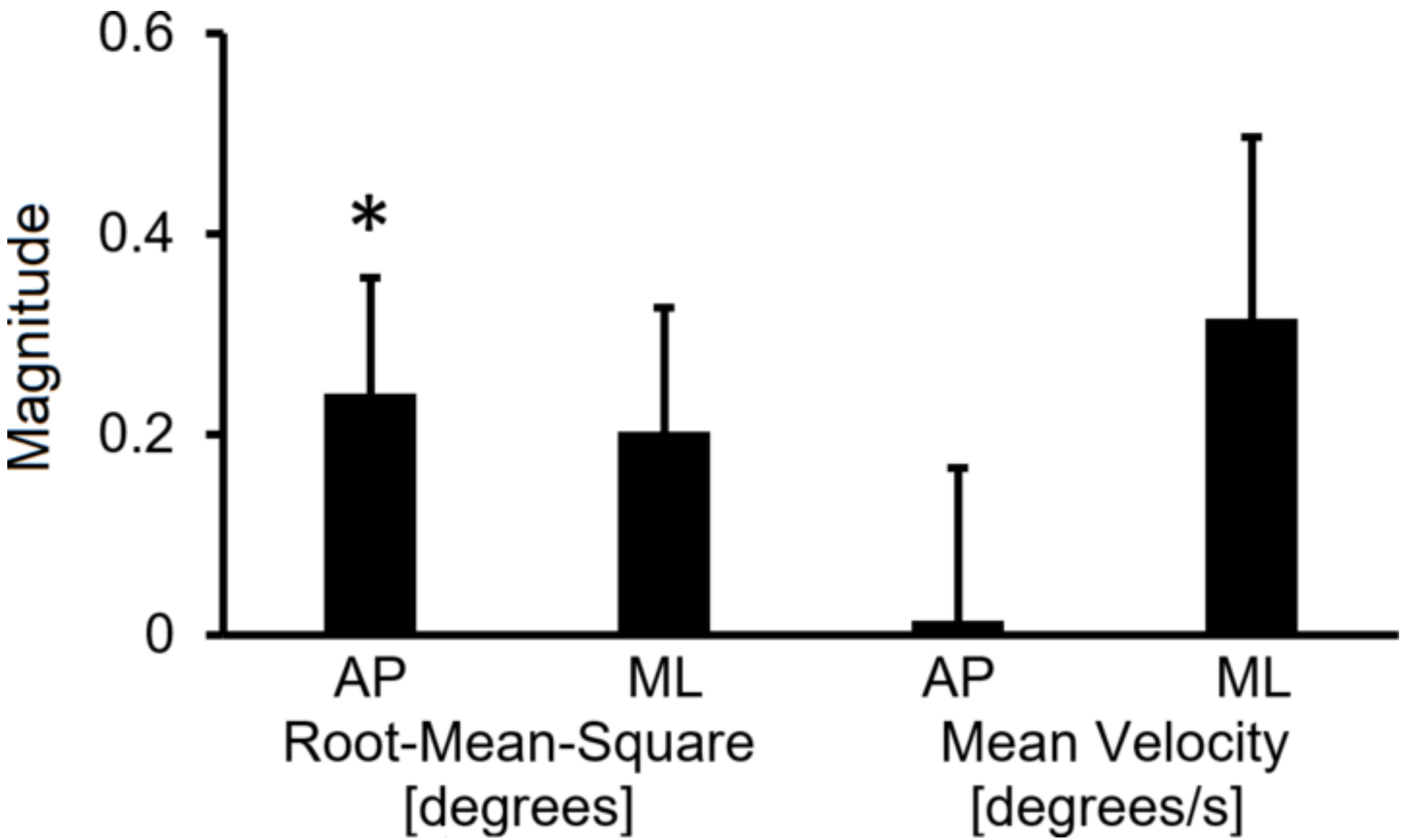

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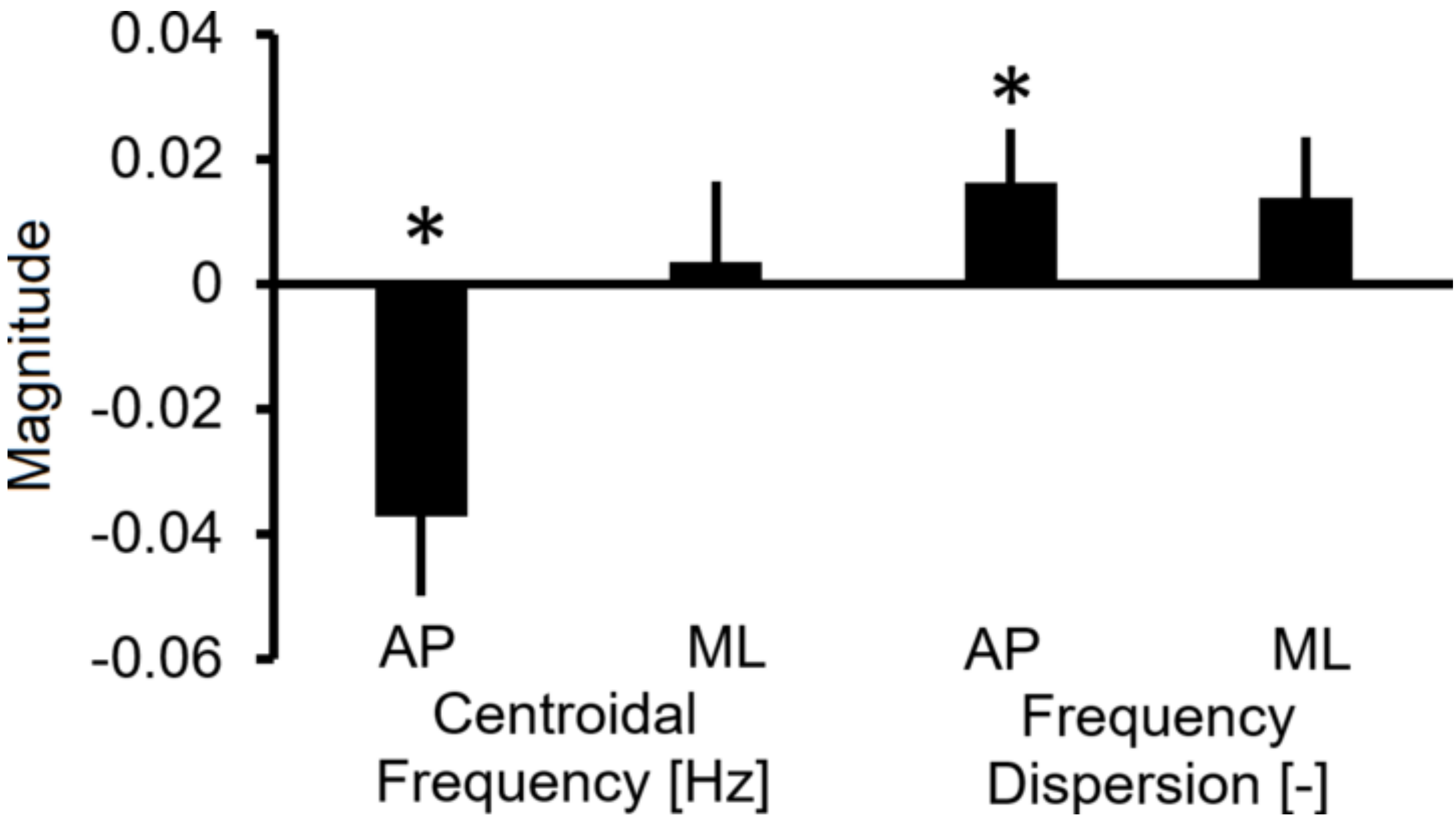
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Dispersion [-]

Figure 9

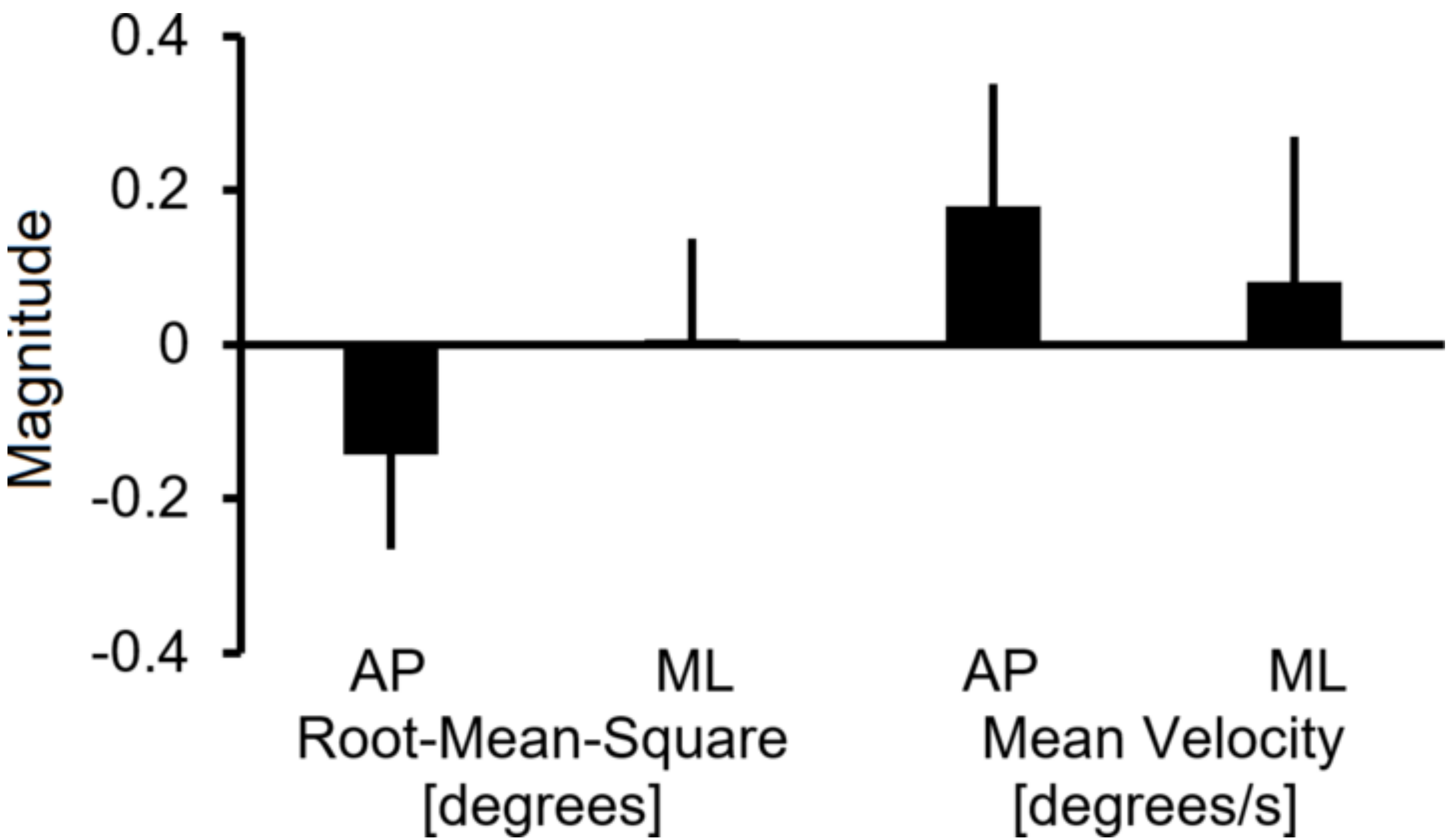
0.4
0.2
0
-0.2
-0.4
Magnitude
AP
ML
AP
ML
Root-Mean-Square
[degrees]
Mean Velocity
[degrees/s]

Figure 10

Click here to access/download;Figure;JoVE_58611_Fig10_Editorial.tif

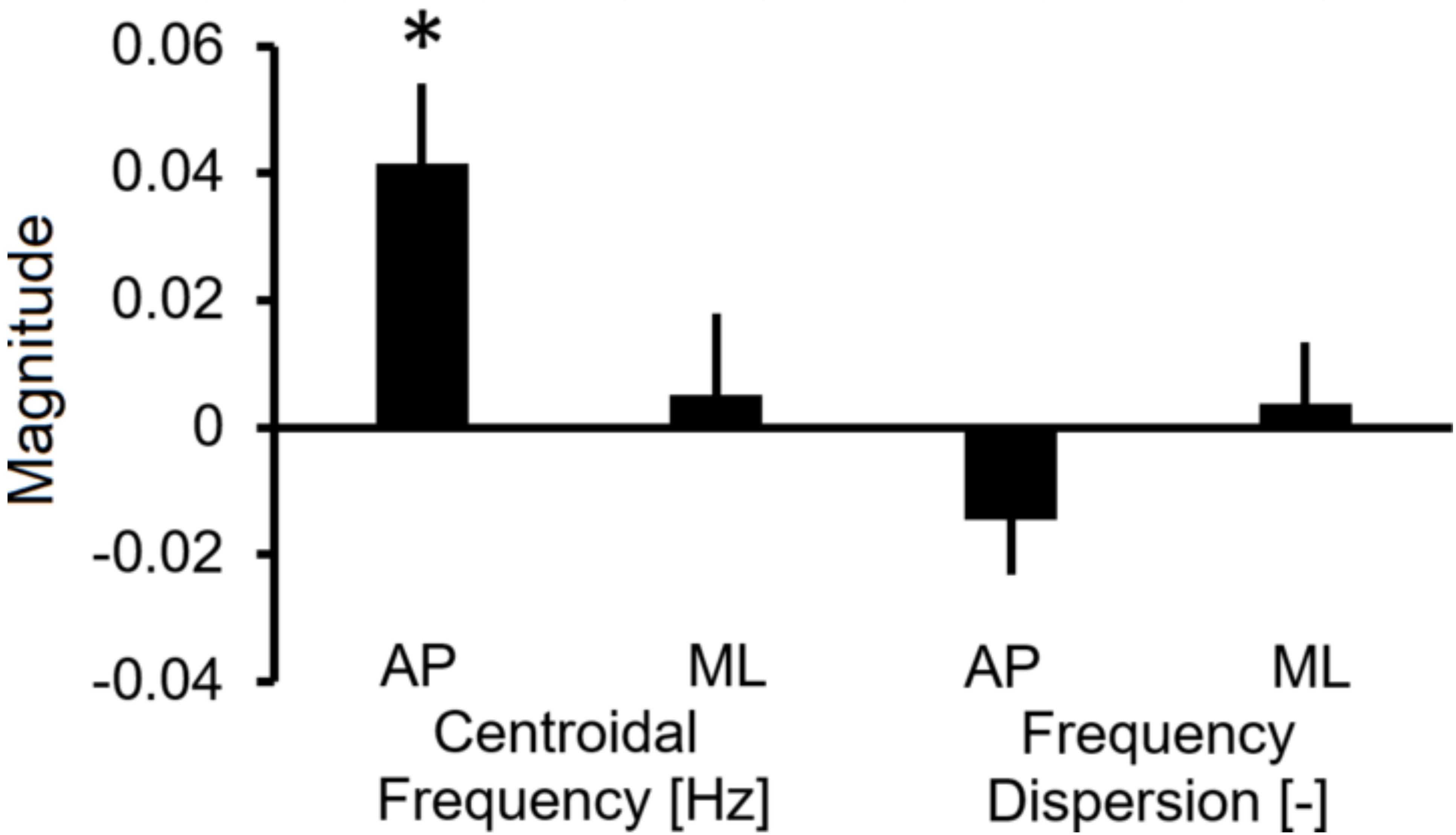

Table 1

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	Radius of curvature (cm)	
Most stable	25	Less difficult to balance
	20	
	15	
	13	
Least stable	11	More difficult to balance

Table 2

Click here to access/download;Table;JoVE_58611_Table2_R2.xlsx

Posturographic Measure	Tilt Direction	Experimental Condition			
		Eyes Open Very Unstable Surface		Eyes Closed Mildly Unstable Surface	
		Vibration Off	**Vibration On**	**Vibration Off**	**Vibration On**
Root-Mean-Square	**Antero-Posterior**	1.60	1.62	2.01	1.70
[degrees]	**Medio-Lateral**	1.53	1.61	1.80	1.74
Mean Velocity	**Antero-Posterior**	2.75	3.01	2.85	2.94
[degrees/s]	**Medio-Lateral**	3.04	3.14	3.38	3.44
Centroidal Frequency	**Antero-Posterior**	0.418	0.449	0.370	0.423
[Hz]	**Medio-Lateral**	0.462	0.467	0.465	0.471
Frequency Dispersion	**Antero-Posterior**	0.659	0.654	0.685	0.661
[-]	**Medio-Lateral**	0.651	0.651	0.662	0.669

Name of Material/ Equipment	Company	Catalog Number
Chassis	McMaster-Carr	8657K421
Lid	McMaster-Carr	8657K414
Base	McMaster-Carr	8657K414
Grip-Tape	McMaster-Carr	6243T471
Base Nut	McMaster-Carr	90596A039
Weld Plate	McMaster-Carr	1388K142
Threaded Rod	McMaster-Carr	90322A170
Sleeve	McMaster-Carr	8745K19
Square Flange	McMaster-Carr	8910K395
Hitch	McMaster-Carr	4931T123
Curved Base	McMaster-Carr	8745K48
Hitch Insert	McMaster-Carr	6535K313
Extrusion	McMaster-Carr	6545K7
Clamp	Vlier	TH103A
Footrest	McMaster-Carr	6582K431
Counterwieght	McMaster-Carr	8910K67
Clevis Pin	McMaster-Carr	97245A616
Microprocessor	Arduino	MEGA 2560
Inertial Measurement Unit	x-io Technologies Ltd.	x-IMU
Vibrating Tactor	Precision Microdrives	DEV-11008

Name of Material/ Equipment	Comments/Description
Chassis	Moisture-Resistant LDPE Polyethylene Sheet 1-1/2" Thick, 24" X 24"
Lid	Moisture-Resistant LDPE Polyethylene Sheet 1/4" Thick, 24" X 24"
Base	Moisture-Resistant LDPE Polyethylene Sheet 1/4" Thick, 24" X 24"
Grip-Tape	Nonabrasive Antislip Tape, Textured, 6" Wide Strip, 2' Long, Black
Base Nut	Steel Round-Base Weld Nut, 5/8"-11 Thread Size
Weld Plate	Low-Carbon Steel Sheet 1/16" Thick, 3" X 3", Ground Finish
Threaded Rod	3" 5/16"-18 Medium-Strength Alloy Steel Threaded Stud
Sleeve	Chemical-Resistant PVC (Type I) Rod 1-1/4" Diameter
Square Flange	Low Carbon Steel Bar, 1/8" Thick, 1" Wide
Hitch	Bolt-Together Framing Heavy-Duty Steel, 1-1/2" Square
Curved Base	PVC Rod, 6" Diameter
Hitch Insert	Bolt-Together Framing Heavy-Duty Steel, 1" Square
Extrusion	1045 Cold Drawn Steel Square Bar Stock, 1' X 1" Wide, Unpolished
Clamp	Adjustable Torque Knob
Footrest	4130 Steel Tubing, 1" X 1" Wide, 0.065" Wall Thickness, Unpolished Mill Finish
Counterwieght	Low-Carbon Steel Rectangular Bar 1-1/8" Thick, 4" Width
Clevis Pin	Zinc-Plated Steel Clevis Pin with Hairpin Cotter Pin, 3/16" Diameter, 1-9/16" Usable Length
Microprocessor	Microcontroller board with 54 digital I/O pins and USB connection
Inertial Measurement Unit	Inertial Measurement Unit and Attitude Heading Reference System with enclosure
Vibrating Tactor	Lilypad Vibe Board, available from SparkFun Electronics

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Title:	Assistant Professor

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Institution: University of Alberta

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Signature: Albert H. Vette

Date: Oct. 12, 2018

*assessment and training

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Response to Editorial Comments:

Thank you very much for the constructive comments, which helped us to significantly improve our manuscript. We have now revised our manuscript according to the editorial comments.

Comment 1: *Step 1.3. – What are its dimensions/specifications?*

Dimensions have been added as requested.

Comment 2: *Step 1.5. – What are the dimensions?*

Dimensions have been added as requested.

Comment 3: *Step 1.6. – Cut using which tools?*

We now indicate that a CNC turning machine should be used for this purpose.

Comment 4: *Step 1.7. – Please provide dimensions on Fig. 3. Unclear what is done to construct it. Please mention material and tools used.*

Dimensions and materials have now been added to this protocol as well as to the caption of Figure 3. We now also refer to the drawings and 3D solid models for detailed part dimensions.

Comment 5: *Step 1.8. – Can you provide an approximate estimate of the length?*

The approximate length has been added.

Comment 6: *Step 2.2. – How is this done? Please state it briefly in the note.*

We now explain the basic calibration method.

Comment 7: *Step 2.2. – What is the range specifically?*

We now state the specific limit on the acceptable vibrational frequency.

Comment 8: *Step 2.2.1. – I do not think there is anything to film here so I am unhighlighting this.*

We agree with this choice.

Comment 9: *Step 3.4.1. – This step lacks filmable content, I recommend unhighlighting it.*

We agree with this choice.

Comment 10: *Step 3.4.1. – How do you define this? Please add this as a note.*

Difficulty is explained in the note, and a reference is made to revised Table 1.

Comment 11: *Step 3.4.1. – How do you define this? Please add this as a note.*

Difficulty is explained in the note, and a reference is made to revised Table 1.

Comment 12: *Step 3.4.1. – Unclear what is done here and what we would show. Please describe exactly what is to be done?*

We hope that re-ordering the protocol has made it clear what is to be done. This was also un-highlighted.

Comment 13: *Step 3.4.2. – This step lacks fimable content, I recommend unhighlighting it.*

We agree with this choice.

Comment 14: *Step 3.4.2. – How are they switched off?*

The tactors can be switched off by toggling the feedback slider in the graphical user interface.

Comment 15: *Figure 2 – Please add dimensions.*

We added dimensions to Figure 2 (JoVE_58611_Fig2_Editorial.tiff)

Comment 16: *Figure 3 – Please add dimensions.*

We agree that dimensions may be useful to the reader. We have added dimensions to the figure caption and also suggest that the reader refers to the drawing files for complete dimensions. In line with good engineering practice, we prefer not to add dimensions to an isometric view of an exploded assembly as they may appear ambiguous to the reader.

Comment 17: *Figure 4 – Please add dimensions. This description pertains only to panel A. Please add a panel description for panel B, indicate the dimensions and also provide a common figure title.*

We agree that dimensions may be useful to the reader. We suggest that the reader refers to the drawing files for complete dimensions. In line with good engineering practice, we prefer not to add dimensions to an isometric view of an exploded assembly as they may appear ambiguous to the reader.

Panel descriptions and a common figure title have been added.

Comment 18: *Figure 5 – Please provide dimensions.*

We agree that dimensions may be useful to the reader. We have added dimensions to the figure caption and suggest that the reader refers to the drawing files for complete dimensions. In line with good engineering practice, we prefer not to add dimensions to an isometric view of an exploded assembly as they may appear ambiguous to the reader.

Comment 19: *Figure 6 – Please remove/replace the commercial name.*

Ok. We have done so.

Comment 20: *Figure 7 – Please add a y axis label to the figure and mention any units (if relevant).*

Y axis is labelled. Unconventionally, the units are listed below the x-axis label, as they differ for each pair of bars. We added the description 'Magnitude' to the y-axis (JoVE_58611_Fig7_Editorial.tiff).

Comment 21: *Figure 8 – Please add a y axis label to the figure and mention any units (if relevant).*

Y axis is labelled. Unconventionally, the units are listed below the x-axis label, as they differ for each pair of bars. We added the description 'Magnitude' to the y-axis (JoVE_58611_Fig8_Editorial.tiff).

Comment 22: *Figure 10 – Please add a y axis label to the figure and mention any units (if relevant).*

Y axis is labelled. Unconventionally, the units are listed below the x-axis label, as they differ for each pair of bars. We added the description 'Magnitude' to the y-axis (JoVE_58611_Fig10_Editorial.tiff).

Response to Editor and Reviewers:

Your manuscript, JoVE58611R1 "Probing and training seated balance with unstable support, motion tracking, and sensory feedback," has been editorially and peer reviewed, and the following comments need to be addressed. Note that editorial comments address both requirements for video production and formatting of the article for publication. Please track the changes within the manuscript to identify all of the edits. After revising and uploading your submission, please also upload a separate rebuttal document that addresses each of the editorial and peer review comments individually.

Thank you very much for handling our manuscript and for inviting us to submit a revised version based on the reviewers' feedback. The comments of the editorial board and reviewers were highly constructive and have helped us to significantly improve the quality of our manuscript. In what follows, we respond to each comment individually and point out respective changes to the manuscript, where applicable. Note that all changes to the manuscript have been highlighted in red to allow their easy identification. We are confident that the revised version of the manuscript addresses all comments and that the content of the manuscript is now acceptable for publication in the *Journal of Visualized Experiments*.

Editorial Comments:

Thank you very much for the constructive comments, which helped us to significantly improve our manuscript. We have now revised our manuscript according to the editorial comments.

Comment 1: *Please expand your Introduction to include the following: The advantages over alternative techniques with applicable references to previous studies; Description of the context of the technique in the wider body of literature; Information that can help readers to determine if the method is appropriate for their application.*

We thank the reviewer for their comment. We now refer to previous studies for context, as well as to highlight that the advantage of our method is the ability to combine existing rehabilitation techniques into a single accessible and portable device (lines 59-61). We have also explicitly described the appropriate applications of our methods (lines 62-64).

Comment 2: *Please note that your protocol will be used to generate the script for the video, and must contain everything that you would like shown in the video.* ***Please add more specific details (e.g. button clicks for software actions, numerical values for settings, etc) your protocol steps.*** *There should be enough detail in each step to supplement the actions seen in the video so that viewers can easily replicate the protocol.*

- *1.1, 1.2: Construct how exactly? Mention equipment used.*
- *1.2, 1.3: Both made of polyethylene?*
- *1.5,1.7: What material I used for the sleeve, cylinders?*

- *1.7: Unclear how the curved surface is prepared.*
- *1.9: Mention specifications of the steel bar.*
- *2.1: Mention specifications for the inertial measurement unit, vibrating tactors etc.*
- *3.1: Mention any exclusion criteria.*
- *3.2.1-3.2.5: For all software-control steps, mention all button clicks and menu selections.*

Thank you for the comment. The equipment used in the construction process included milling machines, turning machines, welding machines, and a bandsaw; these are now mentioned explicitly in the protocol (lines 75-117). We now also list the material type for each part.

In response to this comment and the first reviewer's second major concern, the 3D solid model and drawing files for all parts have been made available, as we agree that this will put the audience of the article in a better position to replicate the structural components. The explicit part dimensions are listed in the respective drawing files. Furthermore, to improve readability, the part dimensions have been removed from the written protocol as they are now redundant. To facilitate the replication of the protocol, we have also:

- included the specifications for the electronic hardware (lines 121-123);
- clarified that the exclusion criteria for participation in the experimental study were neurological disorders, musculoskeletal disorders, and back pain (lines 164-165); and
- included the description of all button clicks for all software steps (lines 184-206).

Comment 3: *Please highlight ~2.5 pages or less of text (which includes headings and spaces) in yellow, to identify which steps should be visualized to tell the most cohesive story of your protocol steps.*

1) *Presumably several of your steps would need to be filmed in a machine shop, please double check the feasibility of filming there.*
2) *Please ensure that the manuscript title best reflects the filmable content (i.e. the portions you highlight).*
3) *The highlighting must include all relevant details that are required to perform the step. For example, if step 2.5 is highlighted for filming and the details of how to perform the step are given in steps 2.5.1 and 2.5.2, then the sub-steps where the details are provided must be included in the highlighting.*
4) *The highlighted steps should form a cohesive narrative, that is, there must be a logical flow from one highlighted step to the next.*
5) *Please highlight complete sentences (not parts of sentences). Include sub-headings and spaces when calculating the final highlighted length.*
6) *Notes cannot be filmed and should be excluded from highlighting.*
7) *Please bear in mind that software steps without a graphical user interface/calculations/ command line scripting (e.g. steps that describe the Arduino programming, 3.3) cannot be filmed.*

Thank you for the detailed instructions. We have made several changes in response to this comment. The highlighted text now includes ~2.5 pages of text forming a cohesive narrative, including all relevant details that are required to complete each step. The highlighted text includes complete sentences only and no notes. In addition, software steps were associated with respective graphical user interface instructions. We have also revised the title to better reflect the highlighted content (lines 3-4).

We are indeed allowed to film in the machine shop, but may not be able to film the actual process of manufacturing the wobble board. Rather, we propose to sequentially move, in the video, from one machine to the next while narrating what has been done at each machine (Protocol Items 1.1 through 1.8) and showing respective components on the finished wobble board.

Comment 4: *JoVE articles are focused on the methods and the protocol, thus the discussion should be similarly focused. Please ensure that the discussion covers the following in detail and in paragraph form: 1) modifications and troubleshooting, 2) limitations of the technique, 3) significance with respect to existing methods, 4) future applications and 5) critical steps within the protocol.*

Thank you for this constructive comment. We have revised the Discussion section to include explicit troubleshooting instructions (lines 339-343). The limitations of the methods pertain to the complexity of relating measured kinematics to balance disorders or improvements (lines 348-349) and the yet unresolved nature of haptic feedback optimization (lines 355-356). The significance with respect to other methods is our device's accessibility and portability, which we now mention explicitly (lines 332-334). We now also list future applications (lines 359-361). Critical steps within the protocol are the selection of task difficulty (lines 336-337) and the configuration of the vibrotactile feedback (lines 355-356).

Comment 5: *Please expand the legends to adequately describe the figures/tables. Each figure or table must have an accompanying legend including a short title, followed by a short description of each panel and/or a general description.*

Thank you for the comment. We have expanded the figure and table legends and included a short title for each. Please see the highlighted changes (red font) in the revised document.

Comment 6: *Please use superscript citation format (edit Lines 262-265, 271-274, 274-286)*

Thank you. We have revised the manuscript accordingly.

Comment 7: *If your figures and tables are original and not published previously or you have already obtained figure permissions, please ignore this comment. If you are re-using figures from a previous publication, you must obtain explicit permission to re-use the figure from the previous publisher (this can be in the form of a letter from an editor or a link to the editorial policies that allows you to re-publish the figure). Please upload the text of the re-print permission (may be copied and pasted from an email/website) as a Word document to the Editorial Manager site* *in the "Supplemental files (as requested by JoVE)" section. Please also cite the figure appropriately in the figure legend, i.e. "This figure has been modified from [citation]."*

Thank you for the comment. We have now obtained permission to re-use two particular figures from a previous publication (Figures 1 and 2 in: Williams, A. et al. Design and Evaluation of an Instrumented Wobble Board for Assessing and Training Dynamic Seated Balance. J. Biomech. Eng. 140, 1–10 (2018)). The permission statements have been included as a PDF document in our submission under the section "Supplemental files (as requested by JoVE)". The file name is: "JoVE_58611_ReprintPermission_ASME_R2".

We have also revised the figure captions of Figures 4 and 6 in the submitted manuscript to include the requested information ("This figure has been modified from Williams et al.[18]"). To adhere to the requirements of ASME, we have also added the following statement: "Republished with permission of ASME, from "Design and Evaluation of an Instrumented Wobble Board for Assessing and Training Dynamic Seated Balance" in the Journal of Biomechanical Engineering, AD Williams, QA Boser, AS Kumawat, K Agarwal, H Rouhani, AH Vette, vol. 140, April 2018; permission conveyed through Copyright Clearance Center, Inc."

<u>Reviewer 1:</u>

Thank you very much for the constructive comments, which helped us to improve our manuscript significantly. We have now revised our manuscript according to the reviewer's comments.

Major Concern 1: *Statistical procedures and experimental details regarding the data presented in the manuscript are unclear. Specifically, it should be make clear if the F-test is referring to the ANOVA analysis? Was repeated measures design used? Is it 2-way (balance conditions and vibration). Moreover, how is the visual information (eyes open/closed) taken into account? And why aren't both conditions presented in data figures (Fig 8-11)?*

We thank the reviewer for their comment – we agree that some further clarification on the statistical procedure would be valuable for the reader. A linear mixed effects model was used to account for the correlation of repeated measurements from each participant. In our model, there are two fixed-effects factors: (1) the balance condition, i.e., the combined effect of changing the eye condition and stability level, as these changes were always carried out concurrently (***although we are aware that they do not need to be, if an experimenter wishes to identify their effects separately; we did so to simplify the analysis for demonstration purposes***); and (2) the vibration condition. In addition to these two fixed-effects factors, the model includes a random-effects factor that varies by participant. The significance of the fixed effects was analyzed by an F-test of the ratio of the variance between group means to the variance of the residuals (ANOVA). We have revised Item 3.4 in the protocol section of our manuscript (lines 225-231), explicitly describing the terms of the linear mixed model and F-test. We have also clarified the use of ‘balance condition’ that combines base difficulty and eye condition (lines 171-179 and lines 242-244).

Major Concern 2: *line 71-121: Section 1: Construction and Assembly of Structural Components section details are thorough, however for someone without machine tools background (e.g., rehabilitation specialists, etc) it may be difficult to replicate the details and instructions outlined. I wonder if there is a more "accessible" way to guide them. Perhaps making the CAD files available may be helpful?*

We thank the reviewer for their comment. We agree that the current description of our procedure may be difficult to replicate for someone without a background in machine tools. In response to this comment, the 3D solid model and drawing files have been made available for all parts – to better guide the replication of the structural components. The explicit part dimensions are listed in the respective drawing files. Furthermore, to improve readability, the part dimensions have been removed from the written protocol as they are now redundant.

Major Concern 3: *line 128: Similarly, it may be of use to provide some sample code for how to "program" the microcontroller? Also, despite the list in the "Table of Materials", it may be useful to refer to the devices (microprocessor, IMU, vibrating devices) in the text here.*

In response to this comment, we have now included sample code for the microcontroller in the revised submission package (‘wobble_board_controller.ino.ino’) – and refer to it in Protocol Item 2.1.1. (line 137-138). In the revised manuscript text, we now also provide details on the used devices (microprocessor, IMU, vibrating devices) as suggested (lines 121-123).

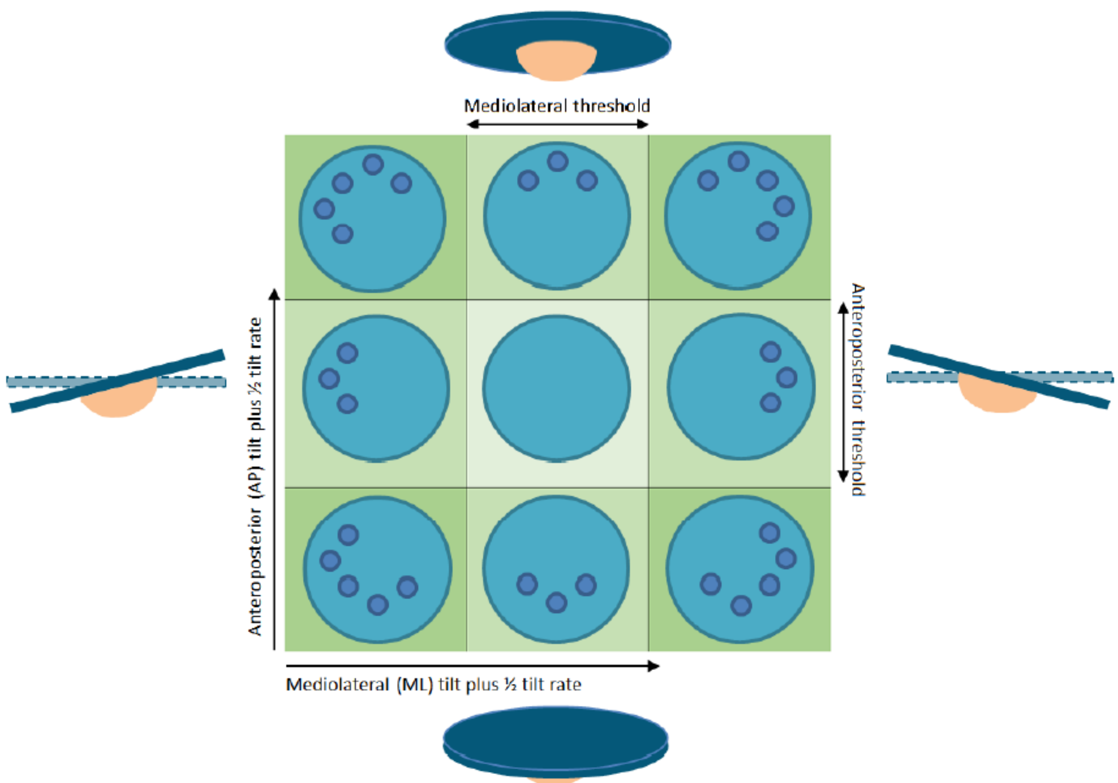
Major Concern 4: *line 195-197: Please clarify details regarding selecting threshold based on "previous performance". Would this would make the system adaptive? And would affect performance during training or intervention? Is this desirable? This is a major concern and should be clarified.*

Thank you for the comment. We agree that further clarification is needed regarding threshold selection. The computed threshold values displayed in the “Q3” column of the Arduino Interface (Figure 6) are equal to the third quartile for each tilt direction (AP, ML) during the previous trial. In Protocol Item 3.2.5., we have clarified the instruction to select a threshold based on the quartile results of the fourth familiarization trial (lines 201-214). Note that four trials have been found to be sufficient to achieve a stable performance of the balance task (Larivière et al. 2013).

Our feedback scheme is based on the notion that balance function is improved when feedback intervention is optimized for each individual (Goodworth, Wall, and Peterka 2009; Loughlin, Mahboobin, and Furman 2011), while providing too much feedback may detriment learning (Marchal-Crespo and Reinkensmeyer 2009). Once the two threshold values have been selected for a given individual, they can be kept constant for that individual to be able to assess improvements over time or with an intervention. In the Discussion section, we address the yet unresolved optimization of haptic feedback design as a limitation of this protocol (lines 355-356).

Major Concern 5: *line 191: "... closest to left, right, front or back....." how does this correspond to the 8 different vibration instruments on the board? Moreover, how did you activate the ones arranged at 45 degrees? Did you calculate the tilt angle somehow?*

Thank you for the comment. The eight enclosures are arranged to accommodate two-, four, or eight-directional configurations. In the current protocol, the overall *tilt direction* (based on AP and ML tilt) was not calculated, and the vibration instruments at 45 degree angles are used only to augment the vibration at the left or right (based on ML tilt) and the front or back (based on AP tilt). This activation scheme was based on the notion that added directional resolution is only as effective as a four-directional tactor configuration for vibrotactile feedback during standing balance (Sienko et al. 2010). The figure below should help to clarify the feedback configuration. We have made revisions to Protocol Item 2.1.1. (lines 137-142) to clarify this procedure for the reader. We specifically state: "The computer activates three tactors closest to the left, right, front, or back of the surface when the control signal exceeds a threshold in that direction, or five tactors if an AP and ML threshold are surpassed simultaneously; none of the tactors are active when the control signal is below the threshold in both directions (i.e., in the no-feedback zone)."



Major Concern 6: *line 226: How were 288 trials analyzed for the 12 participants? Were repeated trials averaged for each condition/participant or not? This is important to ensure p-values are not inflated (i.e., sample size remains n=12). Please clarify.*

Using a linear mixed model, repeated trials are averaged for each condition, and the variance between the group means is compared to the variance of the residuals. The variance between participants is estimated separately, improving the statistical power. As such, the sample size remains n = 12. To clarify this aspect for the reader, we have revised Protocol Item 3.4. (lines 225-231), explicitly describing the terms of the statistical model and significance test.

Major Concern 7: *line 242: Could the effect of vibration, which was shown to increase centroidal frequency be due to the mechanical effect of the vibration rather than the effect on the postural control? Please comment and clarify this important point.*

We thank the reviewer for their comment – this is an interesting question. While the tactors on our device vibrate with a relatively high frequency of 200 Hz, we have found in preliminary static and dynamic tests (using different constant weights instead of seated users) that their activation and activity do not affect the motion of the wobble board. These results agree with the design notion that the tactors were not directly attached to the wobble board, but resting on a locating pin – allowing the tactors to move without influencing wobble board motion.

Minor Concern 1: *line 26-27: It is unclear if the sitting platform "dynamically destabilizes sitting posture" actively (e.g., via actuators) or passively (i.e., since it is a challenging postural tasks / unstable surface). This should be made clear throughout the manuscript (other examples include line 35, line 59).*

Thank you for the comment. We agree that it should be made clear that the sitting platform *passively* destabilizes sitting posture. We have revised this distinction in the manuscript at three different locations (line 26; line 35; line 58).

Minor Concern 2: *Could Fig 8-11 be combined into one figure? Also, could parts of Fig 1-6 also be combined instead of being separated figures?*

Figures 8 to 11 (now: Figures 7 to 10) could potentially be combined, but since each of the bar plots occupies a unique range and scale, we believe that separate figures will help the viewer to understand, at a glance, the differences between conditions. Figures 4 and 5 have been combined into one figure.

Minor Concern 3: *What are the units on the y-axis of Fig 8-11?*

The units are currently listed below the x-axis with the measure description, as they are not consistent for all bars plotted in a given figure (e.g., deg versus deg/s or Hz versus no units).

Minor Concern 4: *Table 1 is unclear. Please elaborate.*

The title of Table 1 was unclear and has been revised to read: "Geometrical properties of the interchangeable bases. The total height of each base module is 63 mm; thus, a base with a smaller radius of curvature, when attached to the device, is less stable than a base with a larger radius of curvature" (lines 320-322).

Minor Concern 5: *line 55: What "protocols" are you referring to?*

Thank you for pointing this out. The protocols referred to were not identified. Line 54 now reads "current sensory feedback methods."

Minor Concern 6: *line 63: it would be useful to add a reference for the "posturographic measures"*

We agree with the reviewer. We now refer to Prieto et al. 1996 (line 62).

Minor Concern 7: *line 153: Why is the size 10x8cm? Is this based on anatomical measures? If so, please use a citation here.*

The tactors were placed so that they will lie under the buttocks of an average-sized person. We now make reference to Churchill and McConville 1976 (line 146).

Minor Concern 8: *line 173: Why 30 second trails? Is this sufficient? Also, please add a reference.*

30-second trials can adequately assess upper body stability, according to Lee and Granata 2008. We now include respective reference (line 168).

Minor Concern 9: *line 177: Again, please add a reference for the eyes open/closed design.*

The point is well taken. We now refer to Silfies, Cholewicki, and Radebold 2003 (line 173).

Minor Concern 10: *line 188: Is "log and monitor" done on the microcontroller or in Labview? Is this done in real-time (one would assume)?*

Yes, the tilt angles are sampled and communicated serially to Labview, where they are logged to a text file, in real-time. Protocol Item 3.3 (line 216) has been revised to read: "The AP and ML signals are automatically stored, in real-time, in a text file for analysis."

Minor Concern 11: *line 196: Please clarify if for example it is possible for front and back simultaneously?*

It is possible for front and left, for example, to be activated simultaneously. However, it is not possible to activate front and back simultaneously. We have revised Protocol Item 2.1.1. to clarify this (lines 137-142). See also the figure above, in response to this reviewer's *Major Concern 5*.

Minor Concern 12: *line 214-216: It would be helpful to provide a brief description of the measures listed here.*

Thank you, we have added a brief description of each measure in Protocol Item 3.3 (lines 216-223).

<u>Reviewer 2:</u>

Summary: *the manuscript is well written and the issue is of importance in spine stability*

We are pleased to hear that the reviewer believes our manuscript is well written and that the underlying study is important in the domain of spine stability. We have provided detailed responses to the reviewer's specific comments below.

Minor Concern 1: *it would be good if the authors refer to wobble chairs in the text*

We thank the reviewer for their comment – we agree that wobble chairs should be mentioned in the text, as they bear resemblance to our device, and their study has guided parts of ours. In our revised manuscript, we explicitly refer to wobble chairs in the Introduction section (lines 59-61) and Discussion section (line 332-334).

Reviewer 3:

Summary: *The device provides an interesting way of challenging and measuring sitting balance.*

We are pleased to hear that the reviewer finds our methods interesting. We have provided detailed responses to the reviewer's specific comments below.

Minor Concern 1: *It appears that Table 2 and the Figures may be redundant.*

We thank the reviewer for their comment – we agree that Table 2 gives the same essential result as Figures 7 to 10 (previously: Figures 8 to 11), so may be redundant. Nonetheless, we feel that readers may benefit by having access to the numerical results in each experimental condition (Table 2) and the differential results depicted by Figures 7 through 10 (previously: Figures 8 to 11).

Minor Concern 2: *Table 2 can't stand alone as abbreviations are not designated.*

Thank you for the comment. Abbreviations in Table 2 have been revised to their full designations.

Minor Concern 3: *References are presented inconsistently.*

We thank the reviewer for their comment. There has been an issue with the citation plug-in, which has now been corrected.

References for Response Letter:

Churchill, Edmund, and John T. McConville. 1976. "Sampling and Data Gathering Strategies for Future USAF Anthropometry." http://www.dtic.mil/docs/citations/ADA025240.

Goodworth, Adam D, Conrad Wall, and Robert J. Peterka. 2009. "Influence of Feedback Parameters on Performance of a Vibrotactile Balance Prosthesis." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 17(4): 397–408.

Larivière, Christian et al. 2013. "Criterion Validity and Between-Day Reliability of an Inertial-Sensor-Based Trunk Postural Stability Test during Unstable Sitting." *Journal of Electromyography and Kinesiology* 23(4): 899–907.

Lee, HyunWook, and Kevin P Granata. 2008. "Process Stationarity and Reliability of Trunk Postural Stability." *Clinical Biomechanics* 23(6): 735–42.

Loughlin, Patrick, Arash Mahboobin, and Joseph Furman. 2011. "Designing Vibrotactile Balance Feedback for Desired Body Sway Reductions." In *Annual International*

Conference of the IEEE Engineering in Medicine and Biology Society, , 1310–13.

Marchal-Crespo, Laura, and David J Reinkensmeyer. 2009. "Review of Control Strategies for Robotic Movement Training after Neurologic Injury." *Journal of neuroengineering and rehabilitation* 6(1): 20–35. http://www.scopus.com/inward/record.url?eid=2-s2.0-68249158648&partnerID=tZOtx3y1.

Prieto, Thomas E. et al. 1996. "Measures of Postural Steadiness: Differences between Healthy Young and Elderly Adults." *IEEE Transactions on Biomedical Engineering* 43(9): 956–66.

Sienko, Kathleen H., Vivek V. Vichare, M. David Balkwill, and Conrad Wall. 2010. "Assessment of Vibrotactile Feedback on Postural Stability during Pseudorandom Multidirectional Platform Motion." *IEEE Transactions on Biomedical Engineering* 57(4): 944–52.

Silfies, Sheri P., Jacek Cholewicki, and Andrea Radebold. 2003. "The Effects of Visual Input on Postural Control of the Lumbar Spine in Unstable Sitting." *Human Movement Science* 22(3): 237–52. http://linkinghub.elsevier.com/retrieve/pii/S0167945703000460.

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