Design of Weight Distribution Monitoring System

Final Design Report

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Abstract

Neurological disorders are a major health issue in the United States. Most people suffering from neurological disorders also develop balance issues. Last semester, a device was fabricated in order to help one hemiplegic individual monitor their lateral balance by providing audio biofeedback. After consulting a physical therapist, it is evident that there exists need for a more general-purpose balance device. Kim Skinner from the Tactile Communication and Neurorehabilitation Laboratory (TCNL) at UW-Madison uses a combination of physical therapy with tongue stimulation for balance training. Here, improvements are proposed to the previous device that will allow subjects to practice balancing with at home feedback. Improvements include adjustable volume, improved casing, and front-back feedback in addition to the previous left-right feedback. This new device aims to supplement physical therapy regimens similar to the TCNL and improve balance retention in these subjects.

Problem Statement

As neurological disorders are becoming more prevalent in the United States, the need for physical therapy is increasing. Most physical therapy regimens for these disorders, such as Parkinson's disease, traumatic brain injury (TBI), and multiple sclerosis (MS), involve extensive balance training. Studies have shown that the greatest retention in balance comes from continued practice, but therapists do not have the resources to continually train all of their patients.[1] This opens the door for a supplemental device to help bridge the gap between therapy sessions. Here, the design of a portable device that will allow subjects to practice proper balance at home is proposed in hopes of greater retention of balance training between sessions.

Background Information

Neurological disorders, including Parkinson's disease, multiple sclerosis, traumatic brain injury (TBI), and stroke, affect a large portion of the U.S. population. An estimated 800,000 people suffer strokes each year.[1] Furthermore, the prevalence of these disorders has been rapidly increasing due to the aging baby boom population as well as the common occurrence of TBI in soldiers involved with the recent conflicts in the Middle East.[2,3] Each of these disorders is associated with a unique set of symptoms, but nearly all individuals suffering from these diseases develop balance issues.[3]

The most common cause of stroke is the occlusion of an artery within the brain. This results in an inadequate supply of glucose and oxygen to the surrounding tissue, leading to a reduction in oxidative metabolism within the cells. Ultimately, cell death occurs within a few hours of the blood flow restriction.[4] Many stroke survivors experience brain damage that can leave their body permanently disabled, with symptoms ranging from numbness to paralysis. Hemiplegia is a common condition resulting from a stroke. This can have substantial consequences on an individual's motor function including impaired balance, complete loss of ambulation, spasms, muscular atrophy, and osteoporosis.[5]

In 2010 alone, nearly 2.5 million U.S. citizens were diagnosed with TBI.[6] As concussions and traumatic brain injuries from sports, recreational activities, and the war in the Middle East increase, the total number of people afflicted by these maladies only rises. Dizziness and disequilibrium are greatly associated with these conditions, eliciting greater need for physical therapists to treat this growing population.

Many physical therapy methods exist to treat balance disorders, producing results with measured improvements in overall health, fitness, and ambulation in subjects. Types of treatment include effort training, gait training, and muscle training.[5] Due to a large diversity of treatment methods, it is difficult to select an ideal therapy regimen. Still, common underlying themes are present in different regimens. One such theme is consistency; like any exercise regimen, it is important that subjects keep up with their program and do not fall into a cycle of inactivity.[5] As such, an activity must not be exceedingly difficult for an individual to perform, as they may get discouraged.

One new form of physical therapy is currently being investigated by the Tactile Communication and Neurorehabilitation Laboratory (TCNL) at the University of Wisconsin - Madison. This method combines traditional balance training sessions with tactile communication, a means of communicating with the brain via electrical stimulation of the tongue. These systems exhibit potential for improving traditional physical therapy regimens.[7] However, a physical therapist must always be present in order for patients to use these systems. Patients have no way of monitoring their balance when performing physical therapy regimens when away from the clinic. Currently, physical therapists in the TCNL instruct patients to watch themselves in the mirror or to simply stand next to a wall to in order to assess their weight distribution. These are extremely subjective forms of assessment that provide no guarantee of accuracy. From this, it is evident that there exists need for a cheap, portable device capable of providing balance feedback.

In order to provide objective feedback of one's balance, it is necessary to measure force. Force is commonly measured with load cells, which utilize physical deformations in combination with the electrical property of resistance in order to measure an applied load. One specific type of load cell is the cantilever load cell. When a load is applied to the metal cantilever, one surface of the metal is subjected to a tensile force (elongating it), while the other side of the cantilever experiences a compressive force (compressing it).[8] This causes the resistance of the tensile side of the cantilever to increase, while the compressive side decreases in resistance. This arises out of the equation for resistance:

$$R = \frac{\rho * L}{A}$$

in which R is equal to resistance (Ω), ρ is the material property of resistivity (Ω*m), L is the length (m) of the resistive element, and A is the cross sectional area (m^2) of the resistive element.[9] A typical three-lead load cell behaves like this, allowing it to be represented as a pair of resistors in series whose resistance deflections are inversely related. This is also half of a Wheatstone bridge (Figure 1). Typically, R_1 is equal to R_2, which is also equal to R_G. As a load is applied across the load cell, the compressive R_G decreases in value, increasing V_o. Also, it is important to realize that the physical deflections resulting from the load are extremely small, so ΔR and V_o fluctuate by minute amounts. A differential amplifier is then used to measure V_o. By applying various known loads and recording different voltage outputs, a calibration curve can be created, allowing for measurement of future loads.

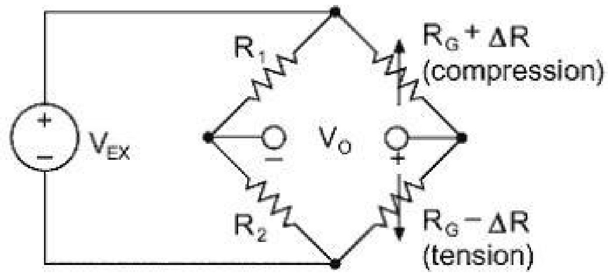

Figure 1: A standard circuit utilizing a half Wheatstone bridge load cell.[8] Fixed resistors R_1 and R_2 are equivalent to the constant resistance R_G of the variable resistors. The variable resistance of the half bridge (ΔR) fluctuates proportionately with an applied load. When an excitatory voltage V_{EX} is applied across the circuit, the output voltage V_O fluctuates proportionately with ΔR.

Design Requirements

The design criteria for this device focus heavily on portability, cost, and convenience. Subjects must be able to easily carry the board with two hands so that they can travel with it. Ideally, the complete system should weigh less than 5 kilograms. The device should be easy to operate for someone who may not have full function of their limbs, as people with neurological disorders commonly have other motor deficits in addition to balance issues. The device should not require the use of any handheld devices during operation, as this may be a distraction and negatively affect balance.

The device must measure four-directional weight distribution and provide corresponding four-directional feedback. It also needs to be able to withstand the weight of an adult (up to 900 N or 200 lbs.) and be less than 5 cm thick. The device should be operable for entire 20-minute intervals, as that is the duration recommended by physical therapists for a typical balance training session. The device should also be loud enough to be heard in an ambient setting (at least 60 dB).[10] The entire system should cost less than $200 to fabricate.

Existing Products

Wii Balance Board

The Wii Balance Board is one of the few commercially available devices that can be used to measure weight distribution (Nintendo, Kyoto, Japan) (Figure 2). It consists of a board with a load cell in each of its four corners. The Wii Balance Board reads the different voltages at each of the four corners and converts them to their respective force values to determine the center of pressure. If a person is leaning to the right, their center of pressure will also shift to the right. A change in center of pressure correlates with a change in weight distribution. This device has been effectively used by institutions for affordable stroke rehabilitation.[11]

Although the Wii Balance Board costs less than $100, it is important to note that the device requires external components for feedback, such as the Wii ($200) with a television or a computer with MATLAB. This is an important factor to consider when portability and cost are important criteria.

Figure 2: Nintendo's Wii Balance Board. The subject stands on the board, and the connected computer or Wii provides visual feedback of the subject's center of gravity via an external screen (monitor or TV). The device can also connect to a smartphone using its Bluetooth technology.

SMART Balance Master

Another device that is clinically used to assess weight distribution is the SMART Balance Master (NeuroCom, San Carlo, CA) (Figure 3). This system is comprised of many different components, including a force plate, two display screens, and a computer. It functions very similarly to the Wii Balance Board in that the force sensors beneath the force plate can be used to measure force and its corresponding weight distribution. It also has moving walls and a moving floor to mimic various conditions as part of an assessment of one's ability to balance.

Similarly to the Wii Balance Board, the SMART Balance Master requires computer software to provide visual feedback. There is also a screen that is incorporated in the device itself for the subject to use while training. One major drawback of the device is its delayed response from the floor to the monitor. When shifting weight distribution, the machine has a half-second delay in response. This lag makes it quite difficult to conduct real-time balance training. Likewise, the device costs upwards of $100,000, so it is not something that can be used in a subject's home.[12] The price and sheer size of this device make it difficult to fit the design requirements for a portable, generalized device.

Figure 3: NeuroCom's SMART Balance Master. The subject stands on the large platform and can use the screen as an aid. The data is fed to a nearby computer that is operated by a physical therapist. The data can be printed or saved electronically and is used to monitor the subject's progress over time.

Previous Design

This project is a continuation from Fall of 2013, when the previous design team created a balance board for a hemiplegic individual who suffered a stroke. She is ambulatory but suffers from balance issues that cause great mental and physical fatigue during standing and walking activities. She requested a device that measures weight distribution and provides her with feedback in order to improve her balance. Because she is hemiplegic, the previous design criteria focused on portability and convenience. The previous device needed to be light enough to be carried with one hand, thin enough for her to step on, and not consist of any external components. Left and right weight distribution was only accounted for, as this client did not require help with her forward and backward balancing.

For the final device, the team used a Health O Meter HDL645KD-63 Glass Digital Scale that consisted of four load cells that can measure force (Figure 4). The two rear load cells in the scale were connected to create a Wheatstone bridge. A circuit was developed to read the load cell output so that shifting the weight distribution to the right induced an upward voltage deflection, while shifting the weight distribution to the left induced a downward voltage deflection. This voltage was supplied by the Arduino Leonardo microcontroller, and the output was then read by the Arduino. The Arduino was programmed to emit one of five frequency tones depending on the measured voltage. The frequencies correlated to notes on a musical scale, centered around 523 Hz, the middle C on a piano (Figure 4).

To operate the device, the subject places it on a flat surface and powers it on. After five seconds, the device plays a short melody indicating that the Arduino has been successfully calibrated. A pulsating middle C tone then plays, indicating that the device measures a balanced weight distribution (or no weight at all). The subject then stands on the device to practice their weight distribution. As they lean to the right, the pulsating tone changes to a constant tone and increases in frequency in relation to a musical scale. As they lean to the left, the frequency decreases. When they are done, they step off the scale and switch off the device.

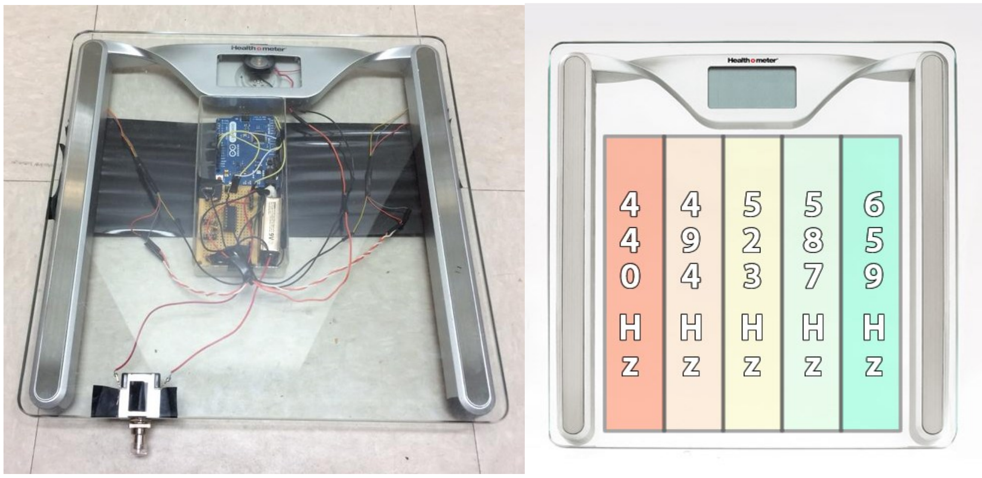

Figure 4: Previous semester's prototype (left) and conceptual diagram of the previous design (right). Colored areas on the diagram indicate "zones" at which the subject's center of gravity of may be when their balance is shifted. A tone of indicated frequency plays in each zone. Center zone consists of a pulsing tone, while the outer zones consist of a constant tone. The device is powered with a 9V battery and includes a switch for convenient on/off functions.

The previous design contained a few flaws. Because the device was fabricated for one client who did not require aid with front and back weight distribution, it is only able to monitor left and right weight distribution. For a more generalized product, it is pertinent that the device be able to compete with the Wii Balance Board in terms of four-directional feedback. Other limitations include poor battery life, crude casing for the circuitry, and inadequate volume for an ambient setting. While this device is functional, there are many suboptimal aspects of its design that need to be improved.

Design Proposal

In order to correct the flaws present in the current device and to generalize the product, the design this semester aimed to optimize the crude casing from previous semester. Likewise, the circuitry was rewired to accommodate more load cells. All audio designs included an audio amplifier and volume dial in order to provide louder, adjustable volume. Therefore, the key criteria to consider for the various designs was the method of front and back feedback, since all of the designs were optimized for the limitations previously discussed and differed mainly in the method of front/back feedback.

Design 1: L/R Audio with F/B Override

This design incorporated the previous design's audio feedback for left/right balance. It added feedback for front/back balance by implementing high-frequency override tones. When the subject's weight distribution was too far forward, left/right feedback would halt, and a new tone would play from the device's speaker (Figure 5). This tone was of a significantly higher frequency than any of the left/right tones so that the subject could easily identify that they were too far forward. Likewise, if the subject's weight shifted too far back, a different high-frequency tone would override the left/right feedback.

Figure 5: Conceptual diagram of first proposed design. New zones were added to the front and back of the scale to indicate a new tone that overrode the five left/right ones. The left/right tones would not play when the subject's weight distribution goes beyond the threshold for front/back balance.

As indicated in Figure 5, the thresholds for beginning front/back feedback were greater than those for left/right feedback. This was partly because the front/back tones would override the others. Using large thresholds for front/back feedback also diminished the effect of improper foot placement on the scale. Additionally, overweight individuals may have additional mass on the anterior or posterior sides of their body, so their center of balance at their normal stance may not be in the same location as that of a normally proportioned individual.

Design 2: L/R Audio with F/B Vibration

The second proposed design also kept the previous model's left/right feedback system. For front/back feedback, vibration would be induced in the subject's foot. This vibration would be caused by small vibration motors attached to the platform of the scale at the front and the back of the foot. Using similar thresholds to the first design, the front motors would vibrate when the subject's weight distribution was too far forwards, and the rear motors would vibrate when the weight distribution was too far backwards (Figure 6). During this vibration, the left/right feedback would still be functional, so the design used two simultaneous modes of feedback.

Figure 6: Conceptual diagram of second proposed design. Left/right feedback would be constant, but the plate would vibrate in the front and the back when weight distribution shifted too far in the respective directions. The tones and plate vibrations could occur simultaneously for a more consistent feedback. The subject should not feel any vibration when within the threshold for front/back balance.

Design 3: LED Matrix

This biofeedback design introduced a small device external to the existing scale (Figure 7). On this device, there would be a grid of LEDs. In a similar manner to the Wii Balance Board, this device would turn on the LED that corresponds to the current center of pressure sensed by the load cells. The device would attach to the scale by a cord, but it would be retractable so that it could be placed on a tabletop or mounted to a wall. The LEDs would directly indicate to the subject their center of gravity and offer the greatest resolution of the four designs. The exact number of LEDs would have been determined by further research if this design was selected. However, foot placement was crucial to the functionality of this device, as even slight imbalances can trigger the feedback.

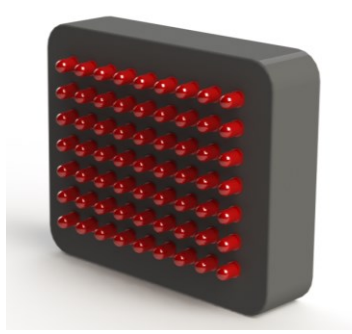

Figure 7: Render of third proposed design. The pictured device would be external to the existing scale and would connect to the scale with a cable. When the subject uses the scale, the device would provide visual feedback. One LED would turn on at a time according to the calculated center of gravity of the subject. As this would provide four-directional feedback, it would replace the existing audio feedback.

Design 4: Touch Tone Audio

The fourth design utilized the biofeedback concepts of the previous device, but it introduced a two-dimensional audio feedback method. The area of the scale was divided into a five-by-five matrix (Figure 8). The left/right (x) axis was assigned a set of frequencies (a, b, c, d, and e; to be determined), while the front/back (y) axis was assigned another (1, 2, 3, 4, 5). Like a touch-tone telephone, two tones played simultaneously depending on the x- and y- coordinates of the subject's weight distribution. This device was also sensitive to foot placement, but less so than the LED design, as it had lower resolution.

Figure 8: Conceptual diagram of fourth proposed design. The scale would divide vertically just as much as it would horizontally, resulting in a grid of 25 zones. Each zone would be assigned two tones depending on left/right (a-e) and front/back (1-5) positions. When the subject's center of gravity was in a particular zone, both of its tones would play simultaneously, resulting in a unique sound for each zone. This functionality would be similar to a touch-tone telephone.

Design Evaluation

The design matrix shown in Table 1 was based on the various biofeedback methods for this generalized balance device. This device was intended for at-home use without a physical therapist present, creating the necessity for it to be easily understood by the patient themselves. If the feedback was too difficult to interpret, it would not offer any advantage over the current subjective methods of at home balance training. As such, ease of use was the most important criterion because the subject must be able to easily interpret the signal and respond accordingly in order to improve their at home training.

The next criterion, acceptable feedback, was based on the comfort level of the subject. Acceptable feedback was defined as the ability to stand on the device and endure the feedback method for increments of at least 20 minutes. It was essential that the subject stay relaxed when balancing and not frustrated or annoyed in order to ensure that they continue to practice with the device. Since this device was intended for individual use, and not a clinical setting, it should also be affordable for the subject. The cost needed to be in the same realm, if not cheaper than the Wii fit balance board, in order to compete in the market.

Ease of fabrication was determined by approximate estimations of how many weeks it would take to fabricate the device. This was important because of the desire for at least two fully functioning prototypes by the end of the semester. Resolution was determined relatively by the number of feedback points given per design (i.e. 25 for touch tone audio, 49 for a 7x7 LED display). This criterion was rated the lowest because this crude device was most likely to supplement a more advanced physical therapy system. Although still important, resolution was not the major concern because posture and foot placement cannot be accounted for with this type of device. This could lead to inaccuracies with all designs, leading to the decreased design criteria weighting.

Criteria	Weight	Design 1	Design 2	Design 3	Design 4
Ease of Use	35	5 (35)	4 (28)	5 (35)	2 (14)
Acceptable Feedback	20	3 (12)	2 (8)	5 (20)	2 (8)
Cost	20	5 (20)	4 (16)	2 (8)	5 (20)
Ease of Fabrication	15	5 (15)	3 (9)	2 (6)	4 (12)
Resolution	10	2 (4)	3 (6)	5 (10)	4 (8)
Total	**100**	**86**	**67**	**79**	**62**

Table 1: Design evaluation matrix. Criteria were ranked, totaling to 100 points. Each design was scored from 1 to 5 for each criterion, and the scores were then scaled proportionately to the weight of each criterion. After summing the scores, the design with the greatest total score was determined to be the best design for this problem.

The fourth design, touch-tone audio, had the lowest the four options. Its main setback was ease of use and acceptable feedback, which were both rated at 2 points out of 5. To evaluate this concept, the team created a LabVIEW VI consisting of a 5-by-5 grid, where each grid space was assigned a certain beat tone. The VI allowed for navigation through the grid, resulting in different beat tones depending on the current position within the grid. After trying various tone combinations, it was deemed too difficult to differentiate between tones, allowing for misinterpretation of feedback. Even if a user could decipher what each sound meant, it involved a large amount of information to process. Likewise, the front/back aspect of this design might cause problems due to its specificity. The foot placement on the device, if not exactly centered, could cause poor readouts and force the subject to go to extreme measures to try to force themselves into the center readout. This would inhibit the benefits of the device as a supplemental tool. The cost, ease of fabrication, and resolution were not very different from the other scale-based designs, as the hardware was nearly the same.

The second design, left/right audio with front/back vibrational feedback, came in third place. Although it was a simple way to distinguish between two-directional weight distributions, the vibrational motors posed the biggest concern for this model. Not only would it be mildly uncomfortable for the subject to endure vibration throughout the balance regiments, but it also might not be an effective feedback method. For these reasons, the design scored 2 points for acceptable feedback. The nerves in feet are not acute and may not be able to distinguish between the front and back of board. Power consumption of the vibrational motors, as well as the difficulty of incorporating them into the device, also limited this design.

The third design, the LED matrix, would utilize a 2D light gradient in order to show the subject their weight distribution. This method required the fabrication of an external device, dropping its ease of fabrication score to 2. The feedback would be similar to other competing models, but it would also be more expensive and difficult to create. This led to a score of 2 in the cost criterion. Correct foot placement and posture would be required in this design, as well, since it is more specific to front and back balance.

The winning design, left/right audio with audio override for front/back (Design 1), scored the highest overall. It tied the LED matrix with a 5 in ease of use, as two tones with frequencies greatly different from the left/right ones are easy to distinguish. It incorporated a relatively new element by using sound for balance in all directions. This design is cheap because it only requires one speaker, is easy to fabricate, as it only needs additional programming on the Arduino. Therefore, it scored a 5 in both of these criteria. The sound can become annoying at times, so its score in acceptable feedback was reduced to 3. Likewise, since the left/right and front/back system cannot be simultaneously playing, its score in resolution was lower than that of the other audio-based designs. Since it scored the most points in the design matrix, it was selected as the final design.

Final Design

After consideration of the design criteria, as well as the feedback received for the previous design, the team decided to pursue Design 1: the left/right audio with front/back override design. Using an identical Health O Meter HDL645KD-63 from the previous design, a new biofeedback device was created. This time, a third load cell was utilized. The two rear load cells were used to measure left-right weight distribution, and the two left load cells were used to measure front-back weight distribution.

Each half-bridge load cell was connected to the +3.3 V pin on the Arduino and ground, and the outputs were read by two differential amplifiers (one for each measurement). Since the rear load cell on the right side was used for both measurements, its output was connected to a voltage buffer to prevent voltage division between the amplifiers. It was also offset by two parallel 10 Ω resistors (5 Ω of resistance) so that the polarity of the amplifier outputs would always be fixed, as the analog inputs of an Arduino cannot read negative voltages. The two amplifier outputs were read by the Arduino, which then output the appropriate frequency tone at a digital pin. This signal was first attenuated by a sliding potentiometer acting as a volume control. It was then amplified so that the greatest volume set by the potentiometer would saturate the amplifier before it was played by a 0.2 W rated speaker. A schematic of this circuit is shown in Figure 9.

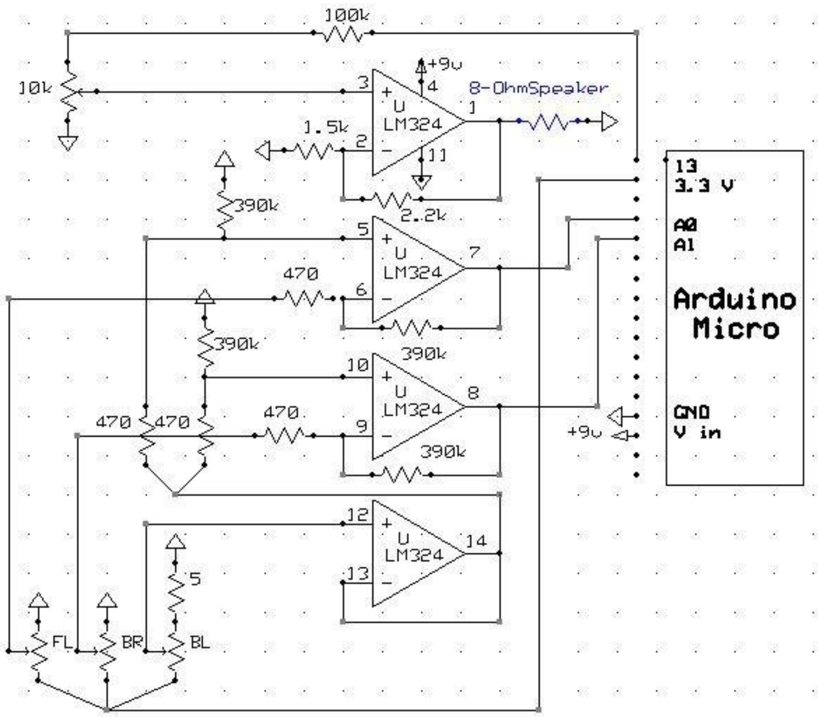

Figure 9: Schematic of the circuit used in the final design. Both the back load cells (BR/BL) were input to differential amplifier to measure left/right weight distribution. Both of the left load cells (BR/BL) were input to differential amplifier to measure front/back weight distribution. The two differential amplifier outputs were then input to an Arduino Micro and simultaneously interpreted in order to determine which feedback tone to play.

To improve on the previous design, an Arduino Micro microcontroller replaced the previously used Arduino Leonardo. The smaller size of the microcontroller helped to minimize the circuit. To further assist with this, the circuit was condensed, and a printed circuit board was ordered from ExpressPCB (Figure 10), replacing the former wire wrap board. After the circuit components were soldered to the board, it was placed inside a small box attached to the underside of the scale. Leads from the load cells, potentiometer, and speaker were attached to the board through a hole cut in the box. This kept almost all of the wires and connections concealed and protected from the subject, reducing the chance of accidental breakage and improving the aesthetics of the device. Instead of battery power, a 9 V DC wall adapter was used. Connected via a barrel plug on the exterior of the scale, this allows the scale to run indefinitely without the need for battery replacement every few hours. Finally, a vinyl decal, consisting of a grid pattern and two foot-shaped outlines, was ordered from FedEx and attached to the face of the scale (Figure 11). The target cost, weight, thickness, and volume outlined in the PDS were met with this design.

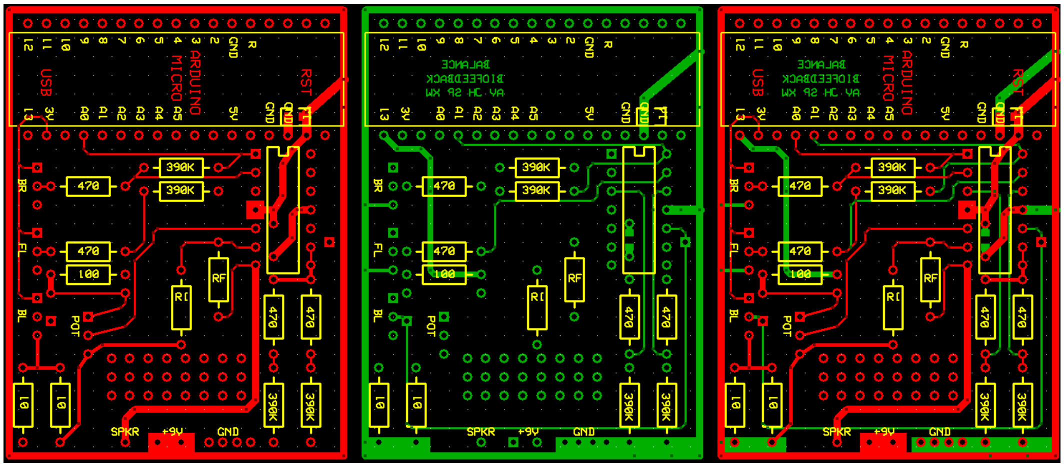

Figure 10: Layout of the PCB ordered from ExpressPCB. Left: The copper traces (red) on the component side of the board. Center: The copper traces (green) on the back of the board. Right: Both sets of copper traces stacked to show connected components. The Arduino Micro would be placed at the top on the component side (red) of the board.

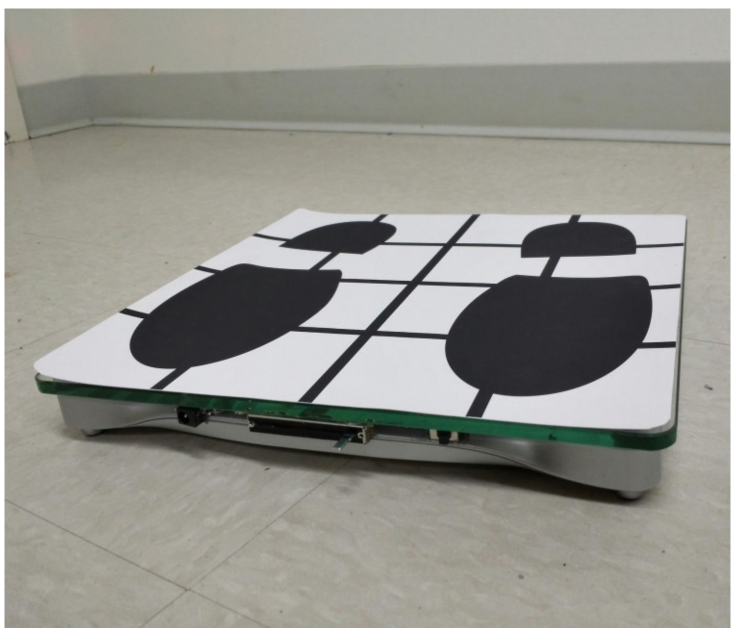

Figure 11: Finished prototype of final design. Vinyl sticker on top guides the subject to proper foot placement on the scale, while the grid assists in evenly adjusting feet if not using the exact outlines. The three user-operated external components (Left-right: power plug, potentiometer to adjust volume, and power switch) are on the front of the scale.

Using the digital values of the differential amplifier outputs, the microcontroller first sets thresholds for determining whether the subject's weight distribution is out of balance. A pulsating 523 Hz tone (the musical note middle C) then begins to play. Afterwards, the two amplifier values are constantly monitored. If the left/right distribution is too far to the left or the right, a constant tone of a lower or higher frequency, respectively, begins to play. There is one more threshold on both sides to step the pitch one more time in the same direction following an even greater shift in weight distribution. However, if the subject's front/back weight distribution shifts too far forward or backwards, the previously playing tone is stopped. It is replaced by a rapidly pulsating tone of frequency 1000 Hz for the front and 2000 Hz for the back. The front/back tones have greater thresholds before activation because a subject's body can influence their normal, "balanced" front/back weight distribution, as the human body is only symmetrical from left to right. Once the front/back weight distribution is back to balanced, the previously playing tone resumes. The full code for the microcontroller is included in Appendix B.

The procedure to operate this device was simplified to increase convenience for the subjects. The device is to be placed on a flat surface and connected to the port for DC power. The device is then turned on, without weight, to allow for initial calibration. After the device calibrates for a few seconds, it will start beeping to indicate that it is functional. The subject can then adjust the volume to his or her preference. After the device is finished operating, the subject may either turn off the switch or simply unplug the outlet.

Experimental Testing

After the circuitry was made to incorporate both front/back and left/right biofeedback, the team conducted experimental testing to verify the accuracy and reliability of the modified bathroom scale. This was done by setting certain weight differentials for the front/back and left/right biofeedback system and measuring the resulting voltage at the amplifier output. A weight differential was defined as the net difference in weight between one side of the scale and another side. For the left/right system, a positive weight differential was defined as the weight placed on the right side minus the weight placed on the left side. Likewise, for the front/back system, a positive weight differential was defined as the weight placed on the front side minus the back side.

The circuitry was connected to the bathroom scale, and the output from the op amp was read by a voltmeter. The team measured the initial voltage before any weights were placed, and then the subsequent voltage after the weights were placed was measured. The weights were placed symmetrically on both sides to only affect one balance system. For example, when testing left/right system, the weights were placed on the left and right side of the scale directly at the center so that the front/back system would read a net weight differential of 0 pounds. For each weight differential, three trials were performed to ensure the reliability of the data.

In addition to three trials of testing, some weight differentials were tested with different sets of weight combinations. For example, the +50 pound weight differential was tested using 50/0, 90/40, and 100/50 pound weights on the right/left side respectively. This allowed for verification of whether different weight combinations that yield the same weight differentials produced the same voltage. In total, combinations of two 50 lb. weights, two 35 lb. weights, two 10 lb. weights, and two 5 lb. weights were used for testing. The results are shown in Figure 12.

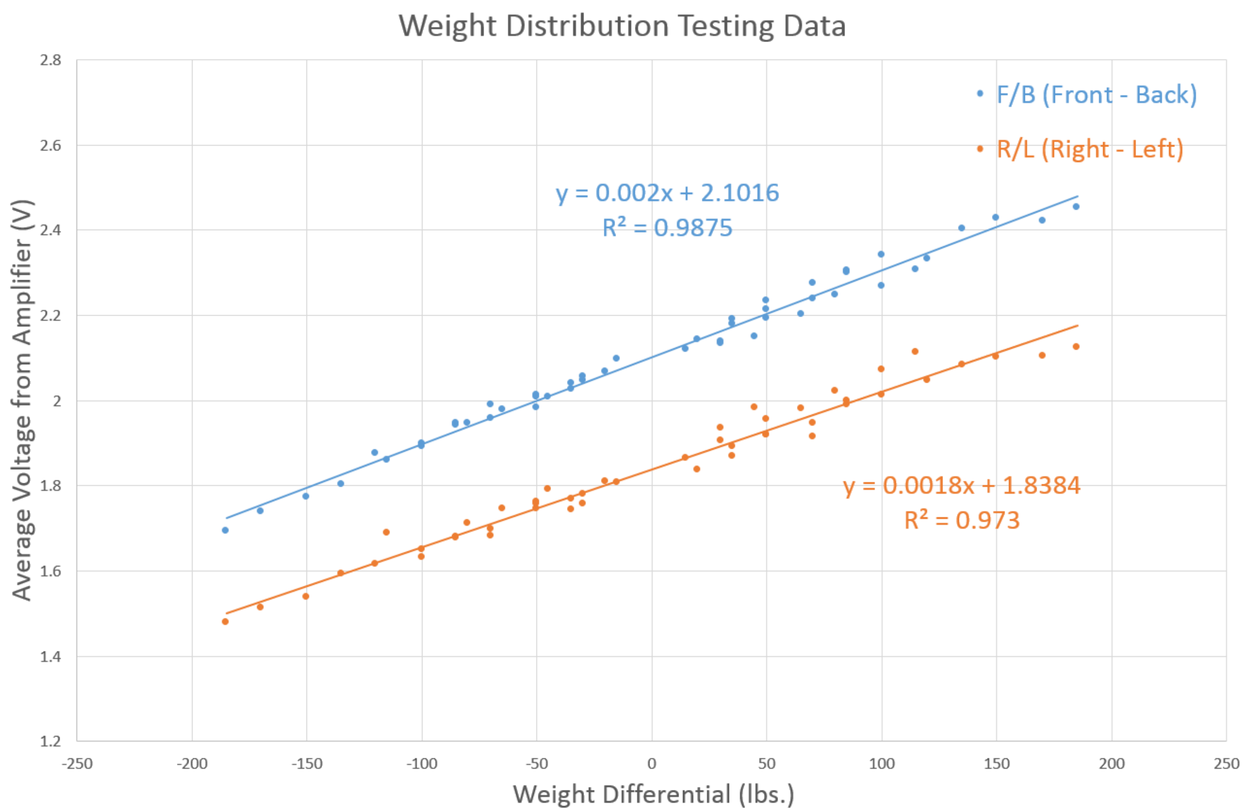

Figure 12: Graph of weight distribution testing data. The x-axis is represented as weight differential in pounds while the y-axis is represented as the voltage output from at the amplified circuit in volts. The dots and line represent the average of 3 trials and the linear trendline for each of the balance systems respectively. Blue signifies data for the front/back balance system while orange signifies data for the right/left balance system. The equations shown are the linear trendline for the data with corresponding coefficient of determination (R^2)

Linear regression lines were made from the data with an average coefficient of determinant value (R^2) of 0.98. This cannot directly indicate the accuracy of the device, but it can be used to assess that the device was fairly accurate and reliable. Using different weight combinations that yielded the same weight differential produced very similar voltage outputs. The only discrepancy noted was that the front/back system had about 0.3 V higher output voltage at each weight differential. This should not pose a problem to the circuitry, as the Arduino code has separate bounds for left/right and front/back systems and can account for the difference. This was attributed to the intrinsic differences in properties of the load cells.

Timeline and Budget

Already having a strong indication of the direction of the continued project in January, research was done to assess the marketability of this potential design. Physical therapists and experts in the balance rehabilitation field were contacted in order to gain insight and feedback on the previous design. After preliminary presentations in February and the final design had been chosen, and parts were ordered. Throughout the month of March, while parts were arriving, the circuit continued to be altered to increase the volume output of the speakers and allow for a variable volume dial. In April, testing began in order to calibrate the device and ensure the precision of the load cells when measuring varying weight distributions. Testing and final prototyping concluded towards the end of April, and the final poster and design were presented on May 2nd. There continues to be talk about making more balance biofeedback boards for Ms. Skinner, and testing will be done over the summer in conjunction with the TCNL lab in order to test the efficacy of this device. An extended timeline is shown in Figure 13.

Task	January		February				March				April				May	
	24	31	7	14	21	28	7	14	21	28	4	11	18	25	2	7
Project R&D																
Lit. Research	X	X	X	X												
Manufacturing							X	X	X	X	X	X	X			
Cost Estimation											X	X	X			
Prototyping												X	X	X		
Deliverables																
Progress Reports		X	X	X	X	X	X	X		X	X		X	X		X
Preliminary Pres.					X											
Final Poster															X	
Meeting																
Client			X	X	X											
Team	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 13: Timeline showing the progress throughout the semester. Highlighted cells indicate plans to work on a task, while Xs indicate that a task was worked on in the given week.

The cost for each device, as shown in Table 2, is detailed below. Each listed part is required to build one functional prototype. If mass produced, the costs would be reduced, but this is the total price for the prototype. Options for other ways to minimize cost include but are not limited to: finding a new scale, designing the PCB board to fit within the scale, eliminating the need for housing, and potentially working with a specialized microcontroller featuring less functionality than the Arduino Micro but still the components needed for the design. These are options to strive for a more affordable design that could be competitive in the balance rehabilitation market.

Component	Quantity	Total Cost
Health O Meter Scale	1	$28.59
Arduino Micro	1	$24.43
LM324 Quad Op Amp	1	$0.57
Potentiometer	1	$1.18
2.2 mm Barrel Jack	1	$2.99
9 V Power Supply	1	$5.95
8 Ω Speaker	1	$5.38
Box for Housing	1	$3.40
ExpressPCB Board	1	$12.93
1x17 Header Pins	2	$2.70
Decoupling Capacitors	3	$1.01
Vinyl Decal	1	$22.50
TOTAL:		**$111.63**

Table 2: Budget list showing the items needed for the final design of one board. Vinyl decal price was not listed because it was unsatisfactory and other options will be explored in the future.

Future Work

While the final design meets the initial criteria for the project, there are several improvements that can be made to it. Primarily, when the prototype was finished, it was found that the thresholds for detecting imbalance are not equivalent for each subject. Because they are based on a flat difference in weight on two sides of the scale, the total weight of the subject is not accounted for. For example, if the thresholds were set expecting a 700 N subject, for which a 20% imbalance would be 420 N on one side of the board and 280 N on the other. If a 900 N subject were to then use the device, the programmed thresholds would trigger when the subject had the same flat weight differential, or 520 N on one side and 380 N on the other. This is now only a 16% imbalance. Therefore, the device must be programmed with thresholds appropriate for the specific target subject.

To correct this problem, the design would incorporate building circuits similar to the one in Figure 9 for each load cell individually. The outputs would be input to four different amplifiers and then to the microcontroller, which would then calculate the subject's weight (based on an established calibration curve) before assigning thresholds proportionate to that subject's weight. Other improvements to the device would include built in or removable memory to track a subject's balance progress throughout a session and over time. This could be interpreted by a physical therapist and add another potential use for the device. Additionally, a rechargeable battery pack would be added to the device, allowing it to be used away from an outlet again without rapidly consuming disposable batteries. Finally, a switch or selector would be built into the device to allow the subject to select from multiple difficulty levels for practicing balance. The more difficult settings would use smaller thresholds for detecting imbalance to make practicing with the device more meaningful for subjects who have improved since they began use.

Conclusion

With an aging population, more people face the reality of balance issues every day due to disorders resulting from stroke, traumatic brain injury, and other conditions. Resulting hospital bills, loss of income, mental health issues, long-term care, and physical therapy sessions can cost individuals from $10,000 to $3,000,000.[13] If at-home training with a device could increase balance retention, reducing the total amount of physical therapy sessions needed by an individual, this board could save individuals thousands of dollars throughout their rehabilitation. The balance biofeedback device aims to affordably supplement physical therapy, bridging the gap between therapy sessions by allowing patients to practice their balance at home.

Acknowledgements

The Balance Biofeedback team would like to acknowledge their advisor, Dr. Thomas Yen, for challenging the team to create a serviceable balance device for the client and for providing support and enthusiasm throughout the design process. The team would also like to thank their client, Dr. Willis Tompkins, for providing support and funding for the design. Thanks are also extended to Kim Skinner for her insight into balance training and providing access to the systems utilized by the TCNL. In addition, we must thank Carol Rohl for inspiring the original project. The team also thanks Professor Michael Morrow of the Electrical and Computer Engineering Department for help with PCB design. Lastly, the team would like to express gratitude to the Department of Biomedical Engineering at the University of Wisconsin - Madison for providing facilities, equipment, and resources.

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Appendix A: Product Design Specifications

Design of Weight Distribution Monitoring System
Product Design Specifications
5/7/2014

Group Members: Jacob Hindt, Andrew Vamos, Shawn Patel, and Xiyu (Steve) Wang

Advisor: Dr. Thomas Yen

Client: Dr. Willis Tompkins

Function: Stroke is a major issue in the United States with more than 800,000 yearly occurrences and 133,000 deaths annually. Many stroke survivors experience brain damage that can result in permanent disabilities, such as hemiplegia. Last semester, a device was fabricated in order to help one hemiplegic individual monitor their lateral balance by providing audio-biofeedback. After consulting a physical therapist, it is evident that there exists need for a more general-purpose balance device, as balance issues are not limited to only hemiplegic individuals but are common with most neurological disorders. Kim Skinner from the Tactile Communication and Neurorehabilitation Laboratory (TCNL) at UW-Madison is using a combination of physical therapy with tongue stimulation in order to train subjects to balance and retain their sense of balance. We are developing a portable device that will allow her subjects to practice proper weight distributions at home. We hope that the device will supplement the physical therapy done at TCNL and allow subjects to have better balance training retention and improve their overall quality of life.

Client Requirements:
- The device must be portable enough to carry with two hands (less than 5 kg)
- The device must be thin, so that a subject can easily step onto the device (less than 5 cm)
- The device must not require the subject to look downwards or hold onto an external object, which can disrupt balance

Design requirements:

1. Physical and Operational Characteristics

a. Performance requirements: The device must be able to perform numerous tests with up to 900 N (200 lbs.) of force.

b. Safety: The device should not present considerable risk of falling or harm to the subject.

c. Accuracy and Reliability: The device should be accurate enough to discern changes in weight distribution but not too precise as the body is never in rest, even when standing. A threshold of 20% will be adapted to allow the subject to practice weight distribution.

d. Life in Service: Physical therapists recommend up to two 20-minute practice sessions per day. To allow for such frequent operation, the device will operate off household wall power to avoid the high costs that might be incurred from battery-powered operation.

e. Shelf Life: The device must be able to be stored and easily retrieved for further use over a period of at least a year.

f. Operating Environment: The device will be used in standard living environments with minimal weather effects. It will be placed on a flat surface and can be operated at room temperature (20-25 °C). The device must be able to grip to a variety of surfaces without the risk of damaging sensitive flooring (i.e. hardwood). As the device is audio-based, the device will be used in an environment with ambient noise up to 60 dB.

g. Ergonomics: There should be minimal user interaction beyond interpreting the biofeedback while using the device. The device will contain two foot-shaped outlines to aid in the subject's foot placement. After the setup is complete, the subject then only needs to stand and attempt to balance using the feedback mechanism.

h. Size: The device length and width must not exceed 50 cm to maintain portability. Additionally, it must be thinner than 5 cm, as some subjects may have difficulty lifting their feet off the ground.

i. Weight: The device must weigh less than 5 kg to maintain portability

j. Materials: The materials must be lightweight yet durable enough to withstand the subject's weight. Device platform material should be rigid to increase accuracy of the measured force.

k. Aesthetics, Appearance, and Finish: The body of the device will be compact and have no external parts that present safety issues.

2. Production Characteristics

a. Quantity: There must be at least one prototype fabricated for the TCNL.

b. Target Product Cost: The device must cost less than $200 to fabricate.

3. Miscellaneous

a. Customer: The device is being created for many patients who all suffer from balance issues.

b. Patient-related concerns: Since the device will be used to supplement physical therapy sessions, it needs to conveniently provide weight distribution analysis for at-home practice.

c. Competition: Similar products have been designed to measure a person's weight distribution. The Wii Balance Board has been proven to be extremely effective in assessing weight distribution. It utilizes four force sensors to calculate the center of a given weight distribution. However, this device is bulky, too tall, and requires external components. Clinically, a few devices are used. One clinical device, the SMART Balance Master®, provides balance retraining in a box-like device on an 18" by 18" force plate through visual feedback on either a stable or unstable support surface and in a stable or dynamic visual environment. However, the device costs $100,000. Other clinical devices, such as the AMTI OR6-6 force plate, use auditory biofeedback. However, this system interfaces with a laptop computer to acquire signals from the sensor and generate a stereo sound, providing body-sway information.

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Appendix B: Microcontroller Code

```
/*
            BME 301 - Balance Biofeedback
            Arduino Code

            created by: Andrew Vamos, Shawn Patel,
            Jacob Hindt, Xiyu (Steve) Wang

            Last updated: 4/30/14
 */

// Define I/O pins
int lrPin = A0;         // Left/Right analog input pin
int fbPin = A1;         // Front/Back analog input pin
int speaker = 13;       // Speaker pin for tone function

// Theshold ints
int lrAvg, fbAvg, frontOv, backOv, lBound1, lBound2, rBound1, rBound2;
int lrVal, fbVal;

void setup() {
     // Allow load cells to rest to normal values after power button is
pressed
     delay(2000);

     // Calibrate load cells, take 3 measurements 500ms apart
     lrAvg = fbAvg = 0;
     lrAvg += analogRead(lrPin);
     fbAvg += analogRead(fbPin);
     delay(500);
     lrAvg += analogRead(lrPin);
     fbAvg += analogRead(fbPin);
     delay(500);
     lrAvg += analogRead(lrPin);
     fbAvg += analogRead(fbPin);
     delay(500);

     // Average measurements to define starting values for analog inputs
     lrAvg = lrAvg / 3;
     fbAvg = fbAvg / 3;

     // Set thresholds for audio zones
     frontOv = fbAvg + 40;
     backOv = fbAvg - 60;
     rBound1 = lrAvg + 20;
```

```
	rBound2 = rBound1 + 40;
	lBound1 = lrAvg - 20;
	lBound2 = lBound1 - 40;
}

void loop() {
	// Read both analog inputs
	lrVal = analogRead(lrPin);
	fbVal = analogRead(fbPin);

	// Front/back override tones
	if (fbVal > frontOv) {
		tone(speaker, 1000);
		delay(150);
		noTone(speaker);
		delay(50);
	}
	else if (fbVal < backOv) {
		tone(speaker, 2000);
		delay(150);
		noTone(speaker);
		delay(50);
	}

	// Play L/R feedback if F/B is balanced
	else {
		if (lrVal > rBound2) {
			tone(speaker, 659);
			delay(250);
		}
		else if (lrVal > rBound1) {
			tone(speaker, 587);
			delay(250);
		}
		else if (lrVal > lBound1) {
			tone(speaker, 523);
			delay(250);
			noTone(speaker);
			delay(300);
		}
		else if (lrVal > lBound2) {
			tone(speaker, 494);
			delay(250);
		}
		else {
			tone(speaker, 440);
			delay(250);
		}
	}
```

```
    // Built-in delay to prevent rapid switching back and forth of tones
    delay(100);
}
```