Design of Weight Distribution Monitoring System

Preliminary 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, we propose improvements 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. We hope that the new device will supplement physical therapy regimens similar to the TCNL and improve balance retention in these subjects.

Problem Statement

With neurological disorders becoming more prevalent in the United States, the need for physical therapy is increasing. Most physical therapy regimens for 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. This opens the door for a supplemental device to help bridge the gap between therapy sessions. Our design group plans to develop a portable device that will allow subjects to practice proper balance at home, in hopes of greater retention 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. 800,000 people suffer strokes each year alone.[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] As such, there exists an increasing need for methods to treat and improve the balance of those suffering from these disorders.

Many physical therapy methods exist to treat balance disorders, exhibiting results with measured improvements in overall health, fitness, and ambulation in subjects. Types of treatment include effort training, gait training, and muscle training.[4] Due to a large diversity among treatment methods, it is difficult to select an ideal therapy regimen. Still, common underlying themes are present in the different regimen. 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.[4] 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 within 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.[5] However, a physical therapist must always be present for subjects to use these systems. Subjects have no way of monitoring their balance when performing physical therapy regimens when away from the clinic. Currently, physical therapists in the TCNL instruct subjects to watch themselves in the mirror or simply stand next to a wall to in order to assess their weight distribution. These are extremely subjective measures 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.

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 they may travel with it. Ideally, the complete system will weigh less than 5 kilograms. The device should be easy to operate for someone who may not have full function of all four 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 Newtons or 200 pounds) and be less than 5 centimeters thick. The device should be operable for entire 20-minute intervals as that is the time 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 decibels).[6] 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 1). It consists of a board with a strain gage in each of its four corners. When a force is applied on a strain gage, it deforms the strain gage and changes its electrical resistance. If a voltage is ran through the strain gage and monitored, one would see deflection in voltage that correlates with the amount of force exerted. The Wii Balance Board takes 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 used by several labs for affordable stroke rehabilitation.[7]

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

Figure 1. Nintendo's Wii Balance Board

SMART Balance Master

Another device that is clinically used to assess weight distribution is the SMART Balance Master (NeuroCom, San Carlo, CA) (Figure 2). 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 correlating 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.

Similar 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 when conducting training. One major drawback of the device is its delayed response from the floor to the monitor. When shifting weight from side to side, the machine has a half second delay in response. This lag makes it quite difficult to conduct real-time balancing training. Likewise, the device costs upwards of $100,000 due to its analysis of balance and posture, so it is not something that can be used in a subject's home.[8] The price and sheer size of this device make it difficult to fit the design requirements for a portable, generalized device.

Figure 2. NeuroCom's SMART Balance Master

Previous Design

This project is a continuation from Fall of 2013 when the group designed 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 to measure her weight distribution and provide her with feedback in order to improve her balance. Because she is hemiplegic, the previous design criteria focused on portability and convenience. We attempted to fabricate a device that was light enough to be carried with one hand, thin enough for her to step on, and not consist of any external components. We also focused on left and right weight distribution as our 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 3). They connected the two rear load cells in a circuit to create a Wheatstone bridge. The load cells worked in a similar manner to strain gages; 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 provided by the Arduino Leonardo microprocessor and also read by the Arduino. The Arduino was programmed to emit one of five frequencies depending on the voltage measured. The frequencies correlated to notes on a musical scale, centered around 523 Hz, the middle C on a piano (Figure 3).

To operate the device, the client would place it on a flat surface and press the switch. After 8 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 an equal weight distribution (or no weight at all). The client then stands on the device to practice her weight distribution. As she leans to the right, the pulsating tone becomes shift to a constant tone and increases in frequency in relation to a musical scale. As she leans to the left, the frequency decreases. She would aim to maintain weight distribution by having a pulsating tone of middle C. When she is done, she would step off the scale and gently press her foot against the button switch to turn it off.

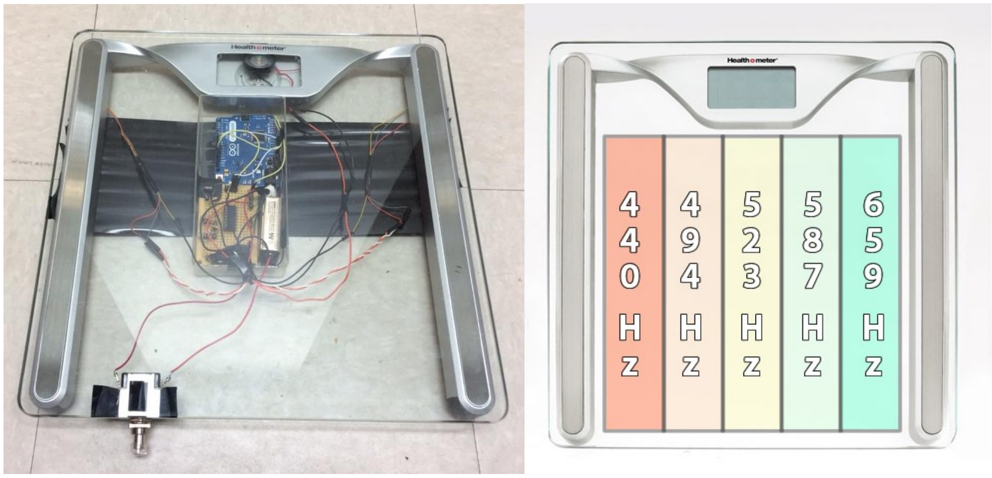


Figure 3. Actual device (left) and conceptual diagram (right) of the previous design. Colored areas on the diagram indicate “zones” at which the subject’s center of gravity of may be when their balance is shifted. Tone of indicated frequency plays in each zone. Center zone consists of a pulsing tone while the outer zones consist of a constant tone.

The previous design contained a few flaws. As the device was fabricated for one client who did not require aid with front and back weight distribution, the device 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 that the previous design suffers from are short battery life, improper casing for the circuitry, improper packaging, and inadequate volume for an ambient setting. While this device was functional, there were 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 will aim to optimize the poor casing and packaging from previous semester. Likewise, the circuitry will be rewired to accommodate four load cells. All audio designs will also include an audio amplifier and volume dial in order to provide greater, adjustable volume. Therefore, the key criteria to consider for the various designs is the method of front and back feedback, since all of the designs will be optimized for the limitations previously discussed and differ mainly in the method of front and back feedback.

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

This design incorporates the previous design's audio feedback for left/right balance. It adds feedback for front/back balance by implementing high-frequency override tones. When the subject's weight distribution is too far forward, left/right feedback halts, and a new tone is played from the device's speaker (Figure 4). This tone is of a significantly higher frequency than any of the left/right tones so that the subject can easily identify that they are too far forward. Likewise, if the subject's weight shifts too far back, a different high-frequency tone overrides the left/right feedback.

Figure 4. Conceptual diagram of first proposed design. New zones are added to the front and back of the scale to indicate a new tone that overrides the five left/right ones.

As indicated in Figure 4, the thresholds for beginning front/back feedback are greater than those for left/right feedback. This is partly because the front/back tones override the others. Using large thresholds for front/back feedback also diminishes 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 a normally proportioned individual.

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

The second proposed design also keeps the current model's left/right feedback system. For front/back feedback, vibration is induced in the subject's foot. This vibration is 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 vibrate when the subject's weight distribution is too far forwards, and the rear motors vibrate when the weight distribution is too far backwards (Figure 5). During this vibration, the left/right feedback is still functional, so the design uses two simultaneous modes of feedback.

Figure 5. Conceptual diagram of second proposed design. Left/right zones are constant, but the plate vibrates in the front and the back when weight distribution shifts too far in those directions.

Design 3: LED Matrix

This biofeedback design introduces a small device external to the existing scale (Figure 6). On this device there is a grid of LEDs. In a similar manner to the Wii Balance Board, this device turns on the LED that corresponds to the current center of pressure sensed by the load cells. The device is attached to the scale by a cord, but it is retractable so that it can be placed on a tabletop or mounted to a wall. The LEDs directly indicate to the subject their center of gravity and offer the greatest resolution of the four designs. The exact number of LEDs will be determined by further research if this design is selected. However, foot placement is crucial to the functionality of this device, as even slight imbalances can trigger the feedback.

Figure 6. Render of third proposed design. One LED turns on at a time according to the calculated center of gravity.

Design 4: Touch Tone Audio

The fourth design utilizes the biofeedback concepts of the current device, but it does so in a new manner to implement two-dimensional audio feedback. The area of the scale is divided into a five-by-five matrix (Figure 7). The left-right (x) axis is assigned a set of frequencies (a, b, c, d, and e; to be determined), while the front-back (y) axis is assigned another (1, 2, 3, 4, 5). Like a touch tone telephone, two tones are played simultaneously depending on the x- and y-coordinates of the subject's weight distribution. This device is also sensitive to foot placement, but less so than the LED as it would have lower resolution.

Figure 7. Conceptual diagram of fourth proposed design. Each zone is assigned two tones depending on left-right (x) and front-back (y) positions. Both tones play simultaneously to indicate two-dimensional weight distribution.

Design Evaluation

The design matrix shown in Table 1 is based on the various biofeedback methods for this generalized balance board. Ease of use is the most important criterion because the subject should be able to easily interpret the signal and respond. This device is intended for at home use without a physical therapist present, creating the necessity for it to be easily understood. The next criterion, acceptable feedback, is based on the comfort of the subject. It is essential that the subject is relaxed when balancing and not frustrated or annoyed to ensure that they continue to practice with the device. Since this device is intended for individual use, it should also be affordable. Ease of fabrication is another factor because of the desire for a fully functioning prototype by the end of the semester. Resolution is the lowest rated, since this is a crude device likely to be supplemental to a more advanced physical therapy system. Although still important, resolution is not the major concern because posture and foot placement cannot be accounted for exactly with this device.

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)	4 (16)
Ease of Fabrication	15	5 (15)	3 (9)	2 (6)	4 (12)
Resolution	10	3 (6)	2 (4)	5 (10)	4 (8)
Total	**100**	**88**	**65**	**79**	**58**

Table 1. Design evaluation matrix. Criteria is ranked, totaling to 100 points. Scores range from 1 to 5 and are scaled proportionately to the weight of each specific criterion.

The fourth design, touch tone audio, had the lowest total of the four. Its main setback was ease of use and acceptable feedback. To evaluate this concept, we 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, which resulted in different beat tones depending on the current position within the grid. After trying various tone combinations, it was decided that it was too difficult to differentiate between tones, allowing for misinterpretation of feedback. Even if a user could decipher what each sound meant, it is a large amount of information to process. Also, the front and back aspect of this design might cause problems due to its specificity. The foot placement onto the device, if not exact, could cause poor readouts and force the subject to go to extreme measures to try and force themselves into the center readout. This would inhibit the benefits of the device as a supplemental tool.

The second design, left/right audio with vibrational front/back feedback, came in third. 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 might not be an effective feedback method, as well. The nerves in feet are not very 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.

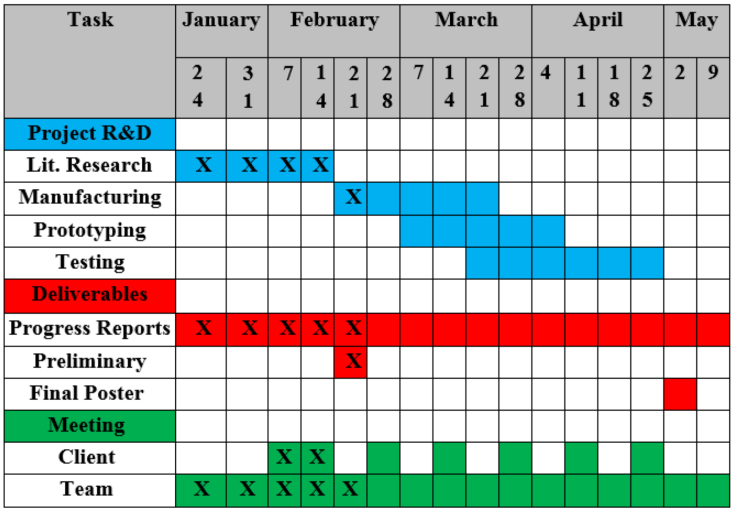
The third design, LED matrix, would utilize a 2D light gradient in order to show the subject where their balance was on the board. It forced the group to either find a projection method that could accomplish this feat, which would be difficult to fabricate, or create an external device. This feedback would be strong for the client and similar to other competing models, but it would also be more expensive and difficult to create. Correct foot placement 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, just seemed to fit the mold for this project. It incorporated a relatively new element by using sound for balance in all directions. This design is cheap because it only requires one speaker and is easy to create with additional programming on the Arduino. The sound should be easy to understand and acceptable for the subject.

Future Work

As illustrated in Figure 8, the design group plans on spending five weeks each on manufacturing, prototyping, and testing. All of the materials will be purchased by the end of February in hopes of creating a functional prototype by March 21st.

Calibration testing will be performed throughout the process to ensure the accuracy of the device. Each load cell will be individually tested for precision by using a set of several weights ranging from five to fifty pounds to create a standard curve in order to compare the load cells amongst each other. Once the calibration curves are created, the load cells will be tested within the balance board with various weights. First, tests will be done with the same total weight but a variation in percentage on each side in order to determine accuracy. Another test will use different amount of weights but keep a constant weight distributions. This will give information on whether the weight distribution voltage fluctuates with different the weight range that this machine can handle.



Task	January		February				March				April				May	
	24	31	7	14	21	28	7	14	21	28	4	11	18	25	2	9
Project R&D																
Lit. Research	X	X	X	X												
Manufacturing					X	🟦	🟦	🟦	🟦							
Prototyping							🟦	🟦	🟦	🟦	🟦					
Testing									🟦	🟦	🟦	🟦	🟦	🟦		
Deliverables																
Progress Reports	X	X	X	X	X	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Preliminary					X											
Final Poster															🟥	
Meeting																
Client			X	X		🟩		🟩		🟩		🟩		🟩		
Team	X	X	X	X	X	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Figure 8. Tentative schedule for the remainder of the semester.

Acknowledgements

The Balance Biofeedback design team would like to acknowledge their advisor, Dr. Thomas Yen, for challenging the team to create a serviceable balance device for the client and 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. Also, we must thank Carol Rohl for inspiring the original project. Lastly, the team would like to express gratitude to the Biomedical Engineering Department of the University of Wisconsin - Madison for providing facilities, equipment, and resources.

References

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[1] Donnan GA, Fisher M, Macleod M, Davis SM. Stroke. The Lancet 2008; 371(9624):1612-23.

[2] Hoffman GJ, Lee J, Mendez-Luck CA. Health behaviors among baby boomer informal caregivers. Gerontologist 2012;52(2):219-30.

[3] Sponheim SR, McGuire KA, Suk Kang S, Davenport ND, Aviyente S, Bernat EM, Lim KO. Evidence of disrupted functional connectivity in the brain after combat-related blast injury. Neuroimage 2011;54 Suppl 1:S21-9.

[4] Ramas J, Courbon A, Roche F, Bethoux F, Calmels P. Effect of training programs and exercise in adult stroke patients: literature review. Ann Readapt Med Phys 2007;50(6):438-44, 430-7.

[5] Danilov YP, Tyler ME, Skinner KL, Hogle RA, Bach-y-Rita P. Efficacy of electrotactile vestibular substitution in patients with peripheral and central vestibular loss. J. Vestib Res 2007;16:119-130.

[6] "Decibel Levels of Common Sounds." *Decibel Levels of Common Sounds*. N.p., n.d. http://home.earthlink.net/~dnitzer/4HaasEaton/Decibel.html

[7] Deutsch JE, Brettler A, Smith C, et al. Nintendo wii sports and wii fit game analysis, validation, and application to stroke rehabilitation. Top Stroke Rehabil 2011;18(6):701-19.

[8] Chien CW, Hu MH, Tang PF, Sheu CF, Hsieh CL, A Comparison of Psychometric Properties of the Smart Balance Master System and the Postural Assessment Scale for Stroke in People Who Have Had Mild Stroke. Arch Phys Med Rehab 2007;88(3):374-380.

Appendix A: Product Design Specifications

Design of Weight Distribution Monitoring System
Product Design Specifications
2/26/2014

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 in most neurological disorders. Kim Skinner from the Tactile Communication and Neurorehabilitation Laboratory 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 our device will supplement the physical therapy done at TCNL and allow subjects to have better balancing 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 10% 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. The device should be able to last a week under battery power. The batteries will be replaceable when exhausted.

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 operated at room temperature (0-50°C).

g. Ergonomics: There should be minimal interaction required while attempting to measure weight distribution. The device will consist of two foot 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 through 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. Possibility of integrating commercial bathroom scale. 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 each person undergoing physical therapy at TCNL

b. Target Product Cost: The device should 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 in supplement with 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 and too tall. 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.

References

http://www.sciencedirect.com/science/article/pii/S000399930500211X
http://resourcesonbalance.com/neurocom/products/SMARTBalanceMaster.aspx
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2577218/?report=classic