Design and Feasibility of a Game-Oriented Balance Board for Rehabilitation Adherence Potential

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***Abstract*—Falls due to balance impairment are a leading cause of injury among older adults, yet routine medical diagnostics often overlook balance assessment. To address this gap, we developed a low-cost, home-based balance board system that combines physical hardware with gamified software to assess and potentially improve users' balance through interactive tasks. Our system integrates load cell sensors with a dedicated computer to track shifts in the user's center of pressure (COP) as they play balance-oriented games. Data from these sessions are automatically visualized and uploaded to a cloud-based dashboard for both users and clinicians. A feasibility study with 10 healthy adult participants was conducted, with results supporting full system functionality and user satisfaction, as well as improved performance across trials. The findings in this paper suggest that the system is not only feasible but could also increase adherence to balance exercises for training and facilitate broader accessibility to balance assessments outside clinical settings.**

Keywords—Balance, Center of Pressure (COP) Tracking, Fall Prevention.

I. Introduction

The human body maintains balance through the complex series of signals that come from the inner ear, sight, and musculoskeletal system [1]. Even a slight disruption in any part of this system can compromise balance, leading to dizziness, instability, or even falls.

These systems will naturally degrade with time, potentially leading to frequent falls amongst the elderly population [2]. These falls are known to be a major cause of morbidity and mortality among the primary target group. An estimated 10% of older adults experience multiple falls within a single year [2]. Primary healthcare providers conduct routine diagnostics and medical exams to determine an individual's overall health. Blood pressure readings, respiration rate, heart rate, hearing tests, and temperature are all standard diagnostic medical exams. However, no routine diagnostic exam focuses on the patient's balance/coordination. Typically, it is not until a person falls that the idea of a fall risk becomes urgent.

Besides aging, ear infections, head injuries, low blood pressure, or inner ear complications can cause young adults to struggle with balance as well [3]. Thus, a deeper understanding of the individual's balance is required to appropriately address fall-related concerns. While balance-related exercises have been shown to significantly improve upon standardized balance scores [4], patient adherence to some physical therapy (PT) exercises are reported to be as low as 42.7% [5]. Increasing adherence to PT exercises, and thereby improving balance, become a topic of interest.

Two examples of devices often used to determine a person's balance (and to perform balance exercises) are BTrackS and BioSway. These are known to be reliable, but they are only intended for diagnostic purposes [6, 7]. These devices tend to be expensive leading to reduced accessibility. An alternative to these expensive devices could be the Nintendo Wii Fit. However, it is primarily gamified and does not provide a set rehabilitation experience or insight on balance towards the user.

We have developed a low-cost and easy-to-use apparatus that may be installed at home and will acquire and store data that the user and clinicians can access. Such a device may potentially be used by healthcare providers as part of general checkups to gain a better understanding of the patient's balance.

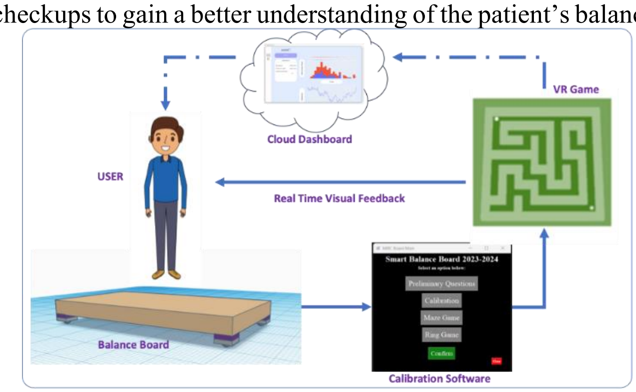

Fig. 1. The user calibrates physical apparatus to their movements, which will then be used to play virtual games. Users receive visual feedback during the game, as well as data-driven feedback after completion.

A single-system approach has been used to create a gamified, interactive balance board (Fig. 1). We can determine a person's range of motion by measuring the shift of their center of pressure. It may also be possible to use the data collected to assess the potential risk of future falls. This long-term goal can be made possible by extensive data collection amongst different populations. We have developed games that include mazes, archery, and a classic ring game. Each game contains a different objective, requiring the user to make different movements on the board to accomplish the task. While the user plays each game, different performance metrics are collected. Some examples include time to complete, exact location of weight, and movement over time. A dashboard has also been created to be paired with this device, storing the variable data and automatically analyzing it. Meaningful visualizations are created to be viewed by the user and the clinical operator of the board. Our primary focus for data collection in this paper revolves around a series of predetermined mazes that the user traversed by leaning in a combination of directions.

To determine whether it is possible to reliably collect data from the developed device, we first conducted a simple validation study, followed by a feasibility study of 10 participants. The participant data was analyzed along with the responses from the feasibility study's exit survey.

II. Methods

A. Hardware

a) Single-Board Computer System: We aimed to create a single-system prototype that will allow a user to play games as well as receive visual feedback from data collected during the game. The computations for the device is performed with a LattePanda V1 (low-cost single board computer) which is connected to load sensors and their respective drivers. As the LattePanda features an onboard ATmega32u4 (Arduino Leonardo), it allows for simple system integration between sensors and the main computer.

b) Sensor Connections: The sensor circuit was based on four 100 kg mini button load cells each connected to their own HX711 load cell amplifier. Each of the load cells was installed on a different corner of the board, and contained within the 'feet' (Fig. 2). Furthermore, a PCB was designed using DipTrace software and fabricated via an inhouse CNC milling machine. The design specifically allowed for the amplifiers to be integrated in the PCB, which in turn is connected to the LattePanda's general purpose input/output (GPIO) pins.

c) Board Design: The main structure for the board is a solid block of wood measuring 0.75" in thickness, 16" in height and 24" in width. A small enclosure for the electrical components is attached to the underside. Each side of the enclosure is precisely cut from wood sheets using a laser cutter, and then joined at the corners using interlacing ends. This was then attached to the underside of the main board using glue. The feet seen at each corner of the board (Fig. 2) are structural components, but for space efficiency and optimal operation, they were custom designed to be compartments that held each of the load cells used to collect readings.

Fig. 2. Additional shell showcasing the underside of the board before introduction of electrical components & LattePanda.

d) Load Cell Housing: The board's feet were designed through SolidWorks, and then realized through 3D printing with polylactic acid (PLA) (Fig. 3). The infill density has been set to be 50% in the interest of reduced printing time and cost. Considering that these parts would need to withstand weight upwards of 250 pounds, a gyroid infill pattern was initially chosen, as previous testing results have shown it to be of a higher relative strength among 3D printing infill patterns [9]. During testing, it was realized that these parts would be compressed primarily in a single axis. Given this information, the infill pattern was later changed to grid, as research shows it has a higher z-axis compressive strength than gyroid [10].

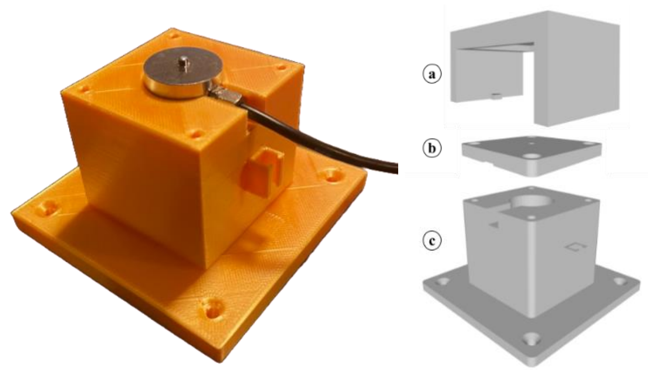

Fig. 3. Realized holder containing button load cell (L) and assembly of load cell container with top piece (a) to face the ground (R).

The button load cell is housed between parts b and c (Fig. 3). To negate long term damage to the 3D printed part, a steel plate is contained between parts a and b (Fig. 3). The button pushes into the plate when force is applied to the board. Four different loads are then continuously sensed at each corner of the board. To capture inputs in individual directions, values from pairs of the load cells are to be compared against one another. For example, the sensed values from the two load cells on the left side of the board are compared to the right side (Fig. 4). The difference between these pairs become inputs, which are calibrated individually toward each user.

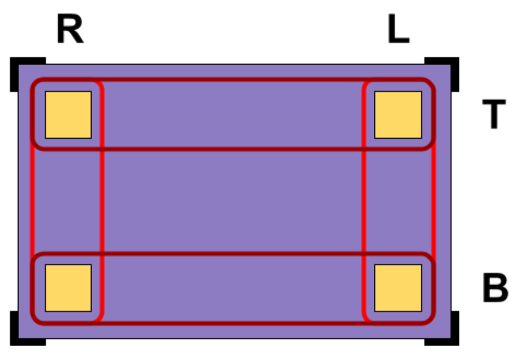

Fig. 4. All 4 combinations used (R, L, T, B), each for the direction correlated to true direction in game.

B. Software

a) Calibration & Movement: Our calibration software takes the average maximum of load cell data in a direction the user is told to lean in (forward, backward, left and right). These averaged maximum values are used as the range boundary for mapping both the x-axis and y-axis. The load cell inputs are then normalized for the user. In other words, depending on how far the user is able to lean comfortably in a given direction, this will serve as the threshold for the game environment. All users will ideally be able to obtain the maximum movement in each singular direction. To minimize any introduced error, games accept 11 markers on each axis. This means that there are 121 unique positions available.

The load cell information is mapped to a range consisting of integer values between -5 and 5 for both x and y axes, with the values being saved as current position variables. These variables are utilized in Ursina: some games use it as a direct input, whilst others use it to determine direction of movement.

The prototype board was to be validated against a standard defined weight (8 kg), which would be placed at exact positions along the surface. The calibration software for the board was used to normalize the outputs on the digital grid, which was used to track the current user position in real time. In calibration, the weight would be placed furthest left, right, top and bottom of the board. Ideally, the digital grid should show furthest left when the weight was placed in such a position. We measured the distance from ideal position to actual position. For example, a target position on the digital grid was the furthest right (X = 5; Y = 0). The actual position that would meet the digital target was (X =1; Y =5). Difference was found by calculating the magnitude of the target position minus that of the actual position, divided by the target magnitude. This was computed for nine positions; two in each direction as well as the origin.

b) Game & Cloud: The game environments for the system were created with Ursina, a game engine that utilizes Python [11], as Python allows for simple usage of serial communication with the ATmega32u4 integrated co-processor. For example, the user can guide a ball to the finish line in a simple maze game (Fig. 5), or have a positional cursor in a game requiring stable posture (Fig. 5). An additional goal was for the cloud to contain static images of all the games, so that it can auto populate them with helpful visual information for any user to make some inferences on their performance. An array of the data would be passed through plotting functions, with both being uploaded to the cloud immediately after each game had completed. As more participants complete the study, general trends can become apparent on performance between specific areas of each maze, as well as performance by age group.

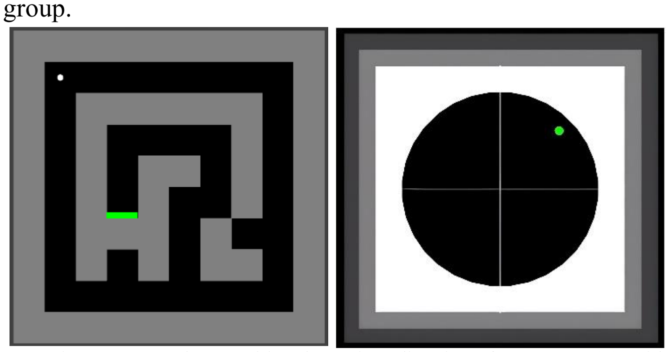

Fig. 5. Game where position determines direction of movement (L), with the other using position as direct input (R).

C. Study Protocol

The study was designed as a cross-sectional feasibility investigation to evaluate the overall usability, accuracy, and participant experience associated with the balance board. Ethical approval for a study with N=10 healthy adult participants was obtained through the University of Rhode Island Institutional Review Board (IRB#2133518). The inclusion criteria for the study required the participants to be 18 years of age or older, be relatively healthy, and self-report with no existing balance complications. After obtaining written consent, the participant will begin the study in the calibration phase.

Participants were instructed to lean upon the launch of the calibration software; they were told to lean (shift their weight), with feet flat on the board, in four directions: forward, backward, left, and right as much as comfortably and safely possible. Each participant would then be instructed to traverse through 3 mazes of increasing difficulty multiple times. Participants would complete a total of 12 mazes by the end of their session. At all points of the session, two members of the study team would be ready on either side in the event of a possible fall. Following the session, the participants complete a questionnaire regarding their experience.

III. Results

Overall, the developed system (Fig. 6) can handle different weights with no visual deformation or damage, suggesting a good upper range of allowable compressive stress. Additionally, we wanted to understand whether the developed system would be capable of use for data collection among users with varying body weights and balance ability. In the following subsections we describe the results of our validation study and the feasibility study.

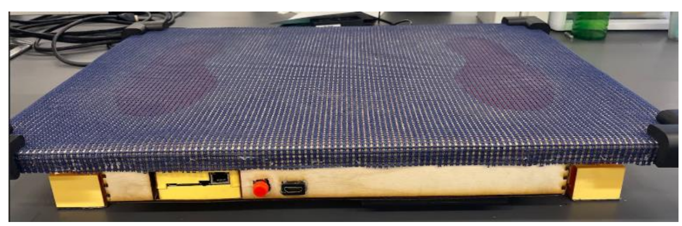

Fig. 6. Completed prototype of the balance board device. Left and right gold-colored objects are 3D printed feet also used as button load cell enclosures (Fig. 3)

A. Validation

The results of our validation study are shown in Table I. It was found that there was an average error of 10.69% in the actual location of the weight (COP) that was computed by our setup. This suggests that in future versions, incorporating higher accuracy load cells might be important to obtain greater accuracy. Errors were considered static, so an initial feasibility study with the current results would be acceptable. Full validation results can be seen below in Table I.

TABLE I. Ideal Versus Measured Real-to-Virtual Position

Ideal (X, Y)	*Measured (X, Y)*	*Difference (%)*
(0, 0)	(0, 0)	0.00%
(2, 0)	(2, 0)	0.00%
(5, 0)	(5, 0.8333)	16.66%
(-2, 0)	(-2, -0.2083)	10.42%
(-5, 0)	(-5.5, -1.875)	16.22%
(0, 2)	(0.25, 2)	12.50%
(0, 5)	(1, 5)	20.00%
(0, -2)	(0, -2)	0.00%
(0, -5)	(-1, -5.208)	20.43%
	Average Error:	**10.69%**

B. *Feasibility Study Outcomes*

With the feasibility study, we wanted to understand the potential of using the developed system among participants to collect balance data and perform the cloud and plotting functions properly and reliably.

To further understand the acceptance of such a device among users we analyzed the responses from our participants. As shown in Table II, evaluation responses for participants after study completion were promising. The results of our feasibility study suggest that the participants generally found the device enjoyable, uncomplicated, as well as easy to control and felt confident in using the device.

TABLE II. USER SATISFACTION EVALUATION QUESTIONNAIRE

Question	*Average (1-5)*
1. I found the device enjoyable	5
2. I found the device unnecessarily complicated	1.3
3. I was able to control the player ball	4.5
4. I felt confident with this device	4.6
5. I found the device easy to use	4.7

C. *Maze Trajectory Plots*

Apart from scoring metrics for completing the maze, our system also recorded the trajectory of the COP over time during the task (Fig. 7). Red paths indicate their 1st time interacting with the maze, while the blue path represents the 4th time through. The "x" along each respective color path depicts every time the participant hits the wall in a location.

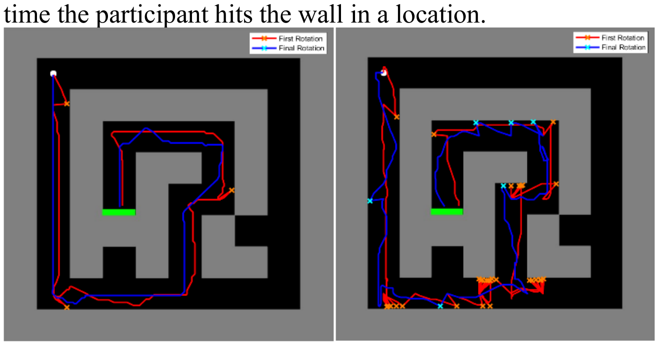

Fig. 7. Comparison between two participants with varying performance levels. An "x" indicates the participant hitting the digital wall.

Participants appeared to perform better in their final rotation compared to the first. Such an observation suggests that there is a component of learning the task that can vary the task performance over the trials. Hence it would be important to consider the effect of learning when using the task performance metrics for evaluating one's balance ability using these task performance metrics.

IV. CONCLUSION

While rehabilitation adherence and balance complications persist as complex issues without a single definitive answer, there exists the ability to mitigate these issues. Participants had generally positive interactions with the board in all reported aspects, showing positive engagement with the system created. With these responses, future works may be considered for using such a system with patients having balance issues. Further conclusions from this study are limited by the number of participants, as well as having no specific population measured. One specific future work for the system itself is to adjust calibration techniques so that the positional error is minimized. This may be done by including a computed offset for the participant's "origin", where the user has their center of pressure exactly between both feet. The long-term focus of the balance board is to allow patients to have the opportunity to safely complete assigned balance exercises in the comfort of their home.

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