Towards Building an Accurate Low-Cost Biofeedback Platform using Force Sensors

Johann Nel, Aaron Dalbeth, Gourab Sen Gupta, Ken Mercer
School of Engineering and Advanced Technology
Massey University
Palmerston North, New Zealand
Email: j.nel@massey.ac.nz, aarondalbeth@hotmail.com, g.sengupta@massey.ac.nz, k.a.mercer@massey.ac.nz

Abstract—**This paper details the design and development of a biofeedback platform. The platform is customizable; it has a load cell slider allowing the user to change the location of the load cells. A 24-bit sigma-delta ADC is used to interface with the load cells, these values are then transmitted to a computer via a microcontroller. The load cell values are extracted and scaled in real-time. The individual load cell weights, total weight and center of pressure is displayed on the computer monitor. Experiments confirm that the load cells and ADC used in the biofeedback platform was highly accurate and responsive. A simple game was then developed, giving the user some physical exercise, also known as exergaming.**

Keywords- biofeedback; load cell; analog-to-digital converter

I. INTRODUCTION

Biofeedback is a set of therapeutic procedures that employ electromechanical systems to measure and provide feedback to patients in the form of audio, visual and haptic signals. The biofeedback process is illustrated in figure 1 where a human receives feedback about the way they undertake a given activity [1].

Biofeedback is valuable for assisting the recovery of individuals with injuries (injured foot for instance) or stroke victims [2]; a biofeedback platform is able to provide feedback to the user increasing their awareness and understanding of their posture (how their weight is distributed when standing) which helps speed up the recovery process [1].

The rest of the paper is organized as follows: Section II reviews the related research of biofeedback systems and exergaming. Section III provides an overview of the system. Section IV covers the ADC programming, how the platform was calibrated, and lastly how the total weight and centre of pressure (COP) was calculated. Section V discusses the results obtained. Section VI covers how the biofeedback platform can be used for exergaming. The paper finishes off with some discussions and conclusions in Section VII.

II. RELATED WORK IN BIOFEEDBACK AND EXERGAMING

Biofeedback has been an area of intense research for several decades [3]. The main idea behind biofeedback is to improve overall health by becoming more aware of involuntary functions such your heart rate, skin temperature, blood pressure etc. [4]. Biofeedback systems have been applied for various applications such as walking gait modification in knee osteoarthritis, balance board for injury rehabilitation, respiratory training, heart rate variability etc.

For biofeedback systems to be effective, data from the platform needs to be send to the computer, processed and feedback needs to be displayed to the user in real-time [5].

The biofeedback platform designed in this paper consists of load cells which measure pressure and can be useful to determine a user's centre of pressure. By making the user more aware of their centre of pressure when standing still, their posture can be potentially improved, improving their overall health.

Exergaming is a term used for video games that are also a form of exercise. It relies on technology that tracks body movement or reaction [6].

Nintendo developed the Wii Balance Board when they released the Nintendo Wii in 2007. The balance board is designed to support people weighing up to 150kg. It makes use of four pressure sensors and measures the user's centre of balance [7]. There are a lot of similarities between the proposed platform and the Wii Balance Board. The Wii Balance Board however is not customizable like the proposed platform.

An example of this can be seen with the addition of the Kinect to the Xbox One, which track the user's movements via cameras, which has enabled a range of games that virtualises physical sports such as bowling, tennis, volleyball, golf and soccer. A player playing any of these games on the console must physically move around the room as they play, and thus undergo cardiovascular exercise while remaining in their own home [1].

III. SYSTEM OVERVIEW

The biofeedback system consists of the following main components: load cells, which are used to transform an applied force into an electrical signal; an analogue-to-digital converter (ADC), which is used to convert the electrical signal obtained from the load cells to a digital signal; a microcontroller to read the digital signals from the ADC and transmit it to a PC via USB for further processing; interface, which is used to convey the information to the user. While conveying information back to the user, it is important to determine what information is useful to user. A system block diagram is shown in figure 2:

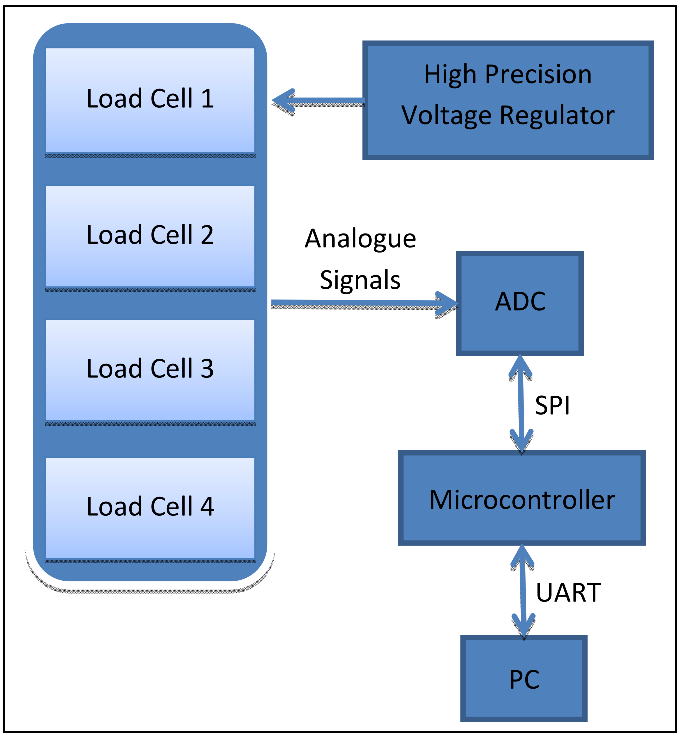

Figure 1: System Functional Block Diagram

A. Load Cell

Load cells can be divided into four main types: beam load cells, column load cells, "S" load cells and finally diaphragm load cells (see figure 3).

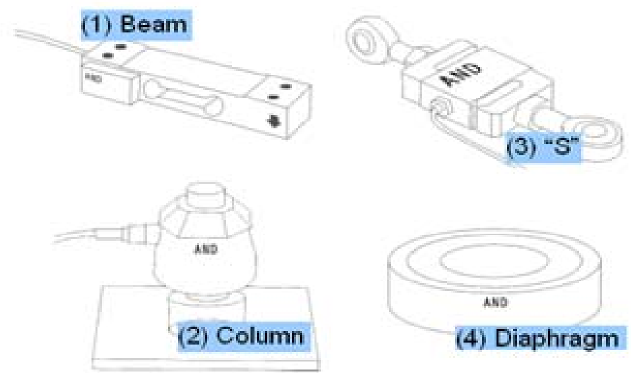

Figure 2: Different Types of Load Cells [7]

When a force is applied to the load cell the strain gauge deforms/stretches which changes the electrical resistance of the wire by an extremely small amount in proportion to the force [8]. Therefore it is extremely important to use a highly stable reference voltage to excite the load cells.

In this project single-point beam load cells are used. The load cells used are ASB1000 manufactured by PT Ltd, and were chosen to handle weights up to 1000kg and their low cost. By reading the datasheet of the ASB1000, the full scale output is 2mV/V ± 0.1% [9]. A high precision voltage regulator was found which outputs 4.096V and was used to excite the load cells. Now this means if 1000kg was being applied to the load cell, an electrical signal of only 8.192mV is being outputted by the load cell. Because there are four load cells in the system it is of utmost importance to check whether the high precision voltage regulator can supply enough current to all the load cells. The current drawn by the load cell is about 10mA. The highest current that could be supplied by the high precision voltage regulator was around 30mA, and the system requires at least 40mA. To increase the current a basic voltage follower circuit was employed; therefore the output current of the high precision voltage regulator was an unimportant factor as the op-amp would supply the necessary current at the same voltage.

B. Analog-to-Digital Converter

It was important to choose an ADC with a very high resolution and low noise due to the fact that the load cells output only 8.192mV at the maximum of load of 1000kg, so the slightest changes had to be detected. The AD7193 by Analog Devices was chosen for the project. It is a low noise, complete analogue front end for high precision measurement applications. It contains a low noise 24-bit sigma-delta analogue-to-digital converter [10]. It has an on-chip low noise gain stage which means that signals of small amplitude can interface directly to the ADC, making it ideal to interface with the load cells. The AD7193 is connected to the microcontroller and is programmed via the Serial Peripheral Interface (SPI) bus. It is possible to program the ADC to have an output rate from 4.7 Hz to 4.8 kHz [10]. It also features an internal clock, temperature sensor, multiplexor, a programmable gain array and an on-chip channel sequencer allowing several channels to be enabled simultaneously. The AD7193 sequentially converts each enabled channel, simplifying communication [10].

Once the high precision voltage regulator, op-amp for the voltage follower circuit and ADC was chosen, a PCB was designed to plug into the microcontroller (see figure 4).

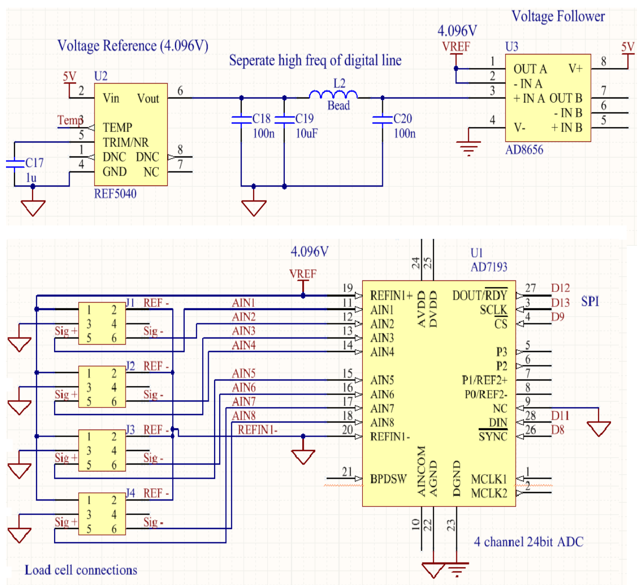

Figure 3: Schematic Diagram for AD7193

Figure 4: Platform with Adjustable Load Cell Sliders

C. Microcontroller and Platform Design

The Arduino Uno development board was used which allowed for rapid development as there is a lot of support and libraries available online. The Arduino Uno features an Atmel ATmega328-PU microcontroller which has UART and SPI busses [11].

The SPI bus is used to communicate with the ADC, and UART is used to send the information obtained from the ADC to the PC, where the information is processed.

The platform was designed so the load cell locations can be easily customized for the best results. It rests on four supports, and the cover is made of 1.6mm steel (see figure 5).

IV. SOFTWARE

The Arduino IDE was used to program the microcontroller, and MATLAB was used on the PC to process the results obtained from the microcontroller. A core function of the platform is to provide accurate, real-time feedback to the user.

A. ADC Programming

The SPI bus is used to program and to communicate to the ADC. All communications to the AD7193 must start with a write operation to the communications register. A flowchart of how to program the AD7193 is shown in figure 5. When the AD7193 powers up or resets, the ADC is in the default state waiting for a write operation to the communications register [10].

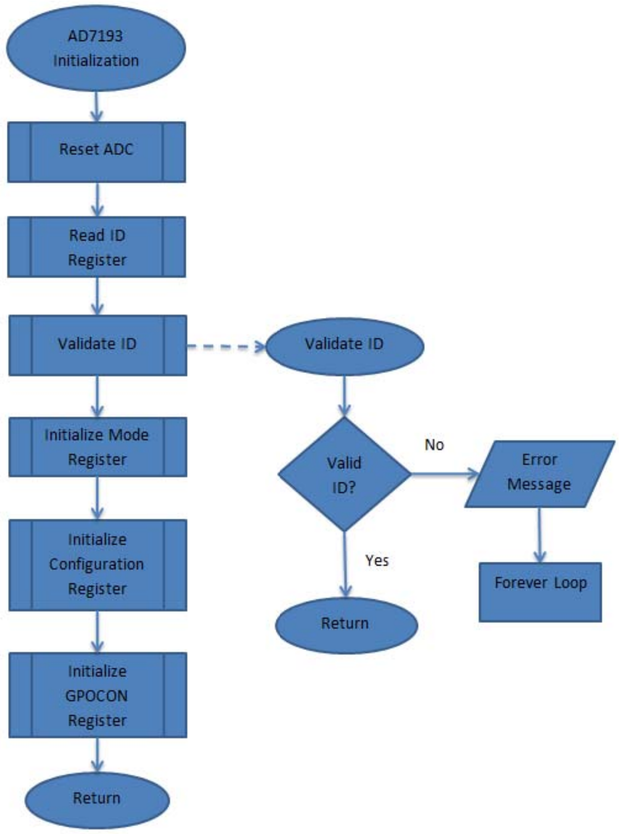

Figure 5: Flowchart of AD7193 Programming

The value 0x60 is written to the communication register letting it know the next operation will be a read and we are selecting the ID register, DOUT will go low to indicate the completion, 0xFF is then written to obtain the value from the ID register (should return a value of 0xX2) and stored in a variable to determine whether the ID is valid or not.

```
// Print message to indicate whether (in)valid ID
   if (ID & 0x0F == 0x02)
        Serial.println("Valid ID");
   else
        Serial.println("Invalid ID");
}
```

Figure 6: ID Validation Code

After it is found that the ID is valid, the mode register (used to select the operating mode, the output data rate, and the clock source) is configured [10]. This is done by writing a 0x08 to the communication register, which selects the mode register and letting it know it will be a write operation. The mode register is a 24-bit register, therefore the ADC expects a 24-bit number, this needs to be send in three bytes.

Once the mode register has been configured the way you want, the configuration register (used to configure the ADC for unipolar or bipolar mode, to enable or disable the buffer, to enable or disable the burnout currents, to select the gain, and to select the analogue input channel) is configured [10]. This is done by writing a 0x10 to the communication register, which selects the configuration register and letting it know it will be a write operation. The configuration register is a 24-bit register, therefore the ADC expects a 24-bit number, this needs to be send in three bytes.

Finally the GPOCON register (used to enable the general-purpose digital outputs) is configured. This is done by writing a 0x28 to the communication register, which selects the GPOCON register and letting it know it will be a write operation. The GPOCON register is an 8-bit register [10].

Once all the registers have been configured, the ADC results can be read, DOUT will go low to indicate the completion of a conversion [10]. The conversion result from the ADC is stored in the data register. The data register is selected by writing 0x58 to the communication register. If the DAT_STA bit in the mode register is set to 1, to contents of the status register (the four LSBs of the status register identify the channel from which the conversion originated) are appended to each 24-bit conversion. The result from each channel is stored in an array called "channel".

The ADC is read four times, as there are four load cells. Once this is done the results obtained from the ADC is send to the PC via UART where the information is processed.

```
Valid ID Found
CH1:8392980 CH2:8398550 CH3:8389737 CH4:8406107
```

Figure 7: Results obtained from ADC being displaying that a valid ID was found and displaying raw ADC results for each channel

B. Calibration

Under no load conditions the ADC values were transferred from the microcontroller to the PC via the serial port. A few hundred of these values where then stored into an array and the mean was calculated. A known weight was then placed on the load cell, where the mean for that weight was calculated, this was then repeated for various weights. The values obtained were then plotted (ADC value vs Weight) to calculate the scaling factor for the load cell. The slope of the linear plot specifies the scaling factor (see figure 7).

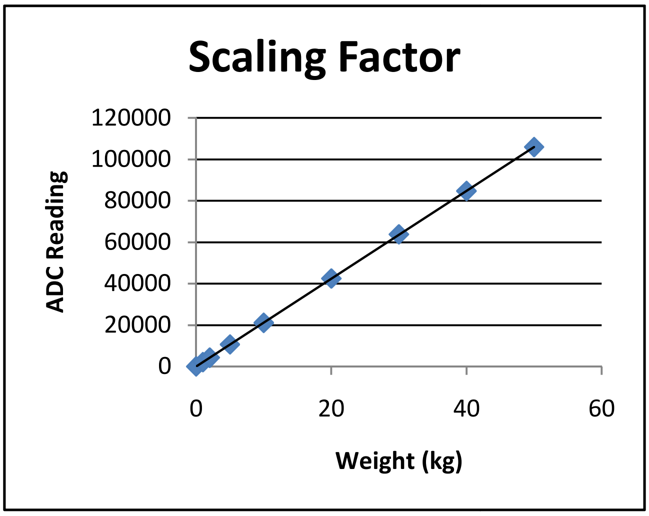

Figure 8: ADC Reading vs Weight

This was repeated for each load cell, as each load cell has a different full scale output. The weight being placed on the load cell can then be calculated (see equation 1).

$$LC = ADC_{Value} - LC_{Mean} \times Scaling\ Factor \quad (1)$$

where:

LC is the load cell value scaled to be in kilogram.
ADC_{Value} is the raw ADC value
LC_{Mean} is the mean value calculated from raw ADC values under no load condition

C. Total Weight

To calculate the total weight on the platform each load cell was tared and the scaling factor was calculated. The total weight is calculated (see equation 2).

$$\sum_{n=1}^{4} Total\ Weight = LC_n \quad (2)$$

D. Center of Pressure

To determine the centre of pressure (COP) location, we observe the data obtained from each load cell (see figure 8).

When the load cells are under load reaction forces are generated, and these reaction forces are F1, F2, F3 and F4. The distance between F1 & F2 and F3 & F4 is Width, and the distance between F1 & F3 and F2 & F4 is Length. The total force is F_{Total} = F1 + F2 + F3 + F4. The COP is equal to X and Y position which can be calculated as follows (see equation 3 and equation 4) [12].

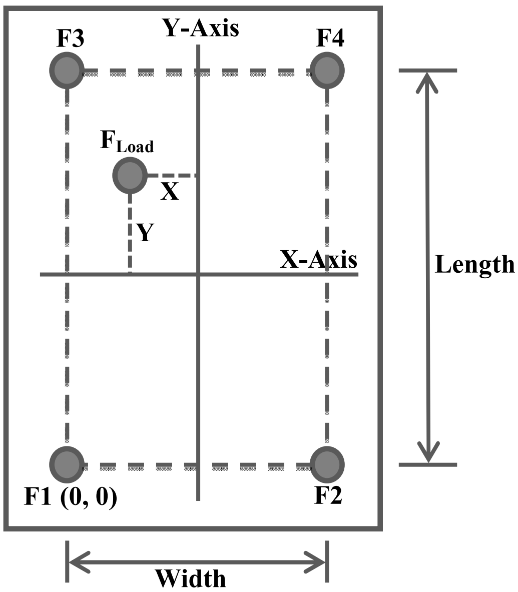

Figure 9: Calculating Centre of Pressure

$$X = \frac{(F2 + F4)}{F_{Total}} \times Width \quad (3)$$

$$Y = \frac{(F3 + F4)}{F_{Total}} \times Length \quad (4)$$

The origin has been defined to be at the lower left corner. When calculating the X-position (equation 3) F2 and F4 are summed together and divided by F_{Total} as the force is shared by all the load cells. This results in a value less than 1, and is then multiplied by the width (distance between F1 and F2) to find the X-position. The same is true when calculating the Y-position (equation 4), except the result is multiplied by the length (distance between F2 and F4).

V. Experiments and Results

A grid was drawn on the platform with 25mm spacing vertically and horizontally (see figure 9). This was done so the load can be placed on known locations to determine the accuracy of the platform.

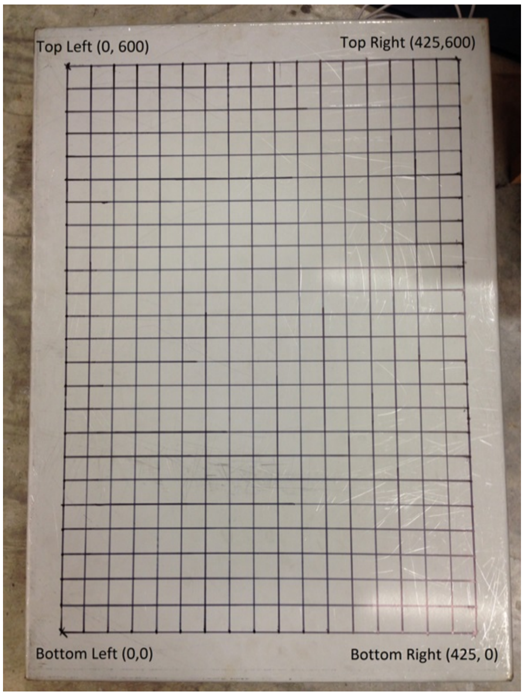

Figure 10: Platform with grid used to measure accuracy of platform

A point load stand was also made to ensure a point load is being placed on the platform (see figure 10).

Figure 11: Weight placed on a point load testing jig

A. Measurement of Position

A known load of 20kg was placed on the point load stand on various locations to determine how accurate the platform can measure the position of the load

Table 1: Mean and Standard Error of X-Position

X-Position	
Mean	1.005mm
Standard Deviation	2.172mm
Minimum Error	-4.279mm
Maximum Error	5.377mm

From table 1 it can be seen that the X-Position mean error is 1.0 ± 2.2mm.

Table 2: Mean and Standard Error of Y-Position

Y-Position	
Mean	0.814mm
Standard Deviation	1.788mm
Minimum Error	-2.437mm
Maximum Error	3.512mm

From table 2 it can be seen that the Y-Position mean error is 0.8 ± 1.8mm.

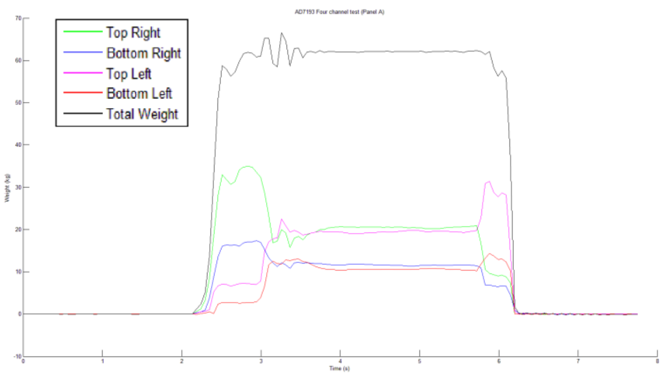

Figure 12: Human being stepping onto and off platform

It can be seen in figure 11 when someone steps onto the platform the smaller signals are the load cell data, and the big signal is the sum of the all the load cells i.e. the total weight.

B. Measurement of Weight

A known weight of 20kg was placed on the platform on various locations to determine how accurate the platform can measure the weight.

Table 3: Mean and Standard Error of Weight

Weight	
Mean	20.087kg
Standard Deviation	0.034kg
Minimum Error	0.024kg
Maximum Error	0.180kg

From table 3 it can be seen that the weight accuracy is 20.09 ± 0.03kg.

VI. Biofeedback Platform used for Exergaming

A simple game was developed in Qt Creator to test the feasibility of using the biofeedback platform for exergaming.

By making use of QCustomPlot, a scatterplot was created with a red cross appearing at a random location on the scatterplot. The user is the blue dot, and the objective of the game was to reach the cross, once the cross has been reached a new cross is generated and plotted at a random location. This resulted in the user having to physical move around on the platform to reach the target giving them some exercise.

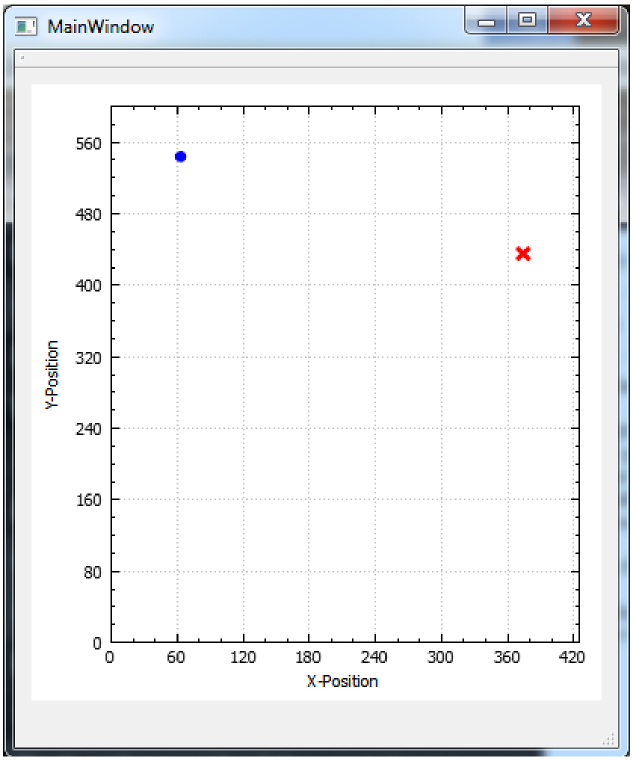

Figure 13: Simple UI displaying the user (blue dot) and their target location (red cross)

There is potential to use the platform for exergaming after creating this simple game. Future work will include creating a scoring system and different game modes.

VII. Discussions and Conclusions

The development of the load cell based biofeedback platform described in this paper will serve as a building block to be used by future engineers in the design and implementation of rehabilitation tools. Potential applications range from sport and exercise research, rehabilitation of leg injuries, patients who underwent hip surgery to determine whether they are walking in a normal fashion, or the creation of exergames [13].

The load cell based platform presented in this paper can be used for exergaming that demands a measure of physical activity from its users [1]. Imagine the platform being larger and on a computer screen or HDTV, a random spot is generated, and the user needs to run to that spot before it disappears to accumulate points. This will not only test the user's reaction speed but also give them cardiovascular exercise.

The following conclusions may be drawn about the performance of this biofeedback platform:

- The load cells used in the platform can withstand weights up to 1000kg each. Meaning if a platform was designed with thicker material the total load can be up to 4 tons and can be applied to various areas.
- The ADC is able to detect very small changes from the load cells enabling the platform to measure weight and position to a very high degree of accuracy.
- The software written in MATLAB is able to give accurate, real-time information to the user about their weight and their centre of pressure.
- The biofeedback platform has the potential to be used for exergaming.
- Overall cost of the system is low (approximately NZ$600)

VIII. References

[1] M. Makwina and G. S. Gupta, "Inclinometer Based Low-cost Biofeedback Balanceboard for Injury Rehabilitation," *IEEE,* pp. 551 - 556, 2014.

[2] D. S. Nichols, "Balance Retraining After Stroke Using Force Platfrom Feedback," *Physical Therapy,* vol. 77, no. 5, pp. 553-558, 1997.

[3] M. Schwarz, P. Olson and F. Andrasik, A historical perspective on the field of biofeedback and applied phychophysocialogy, New York: Guilford, 2003, pp. 3-19.

[4] S. D. Ehrlich, "University of Maryland Medical Center," 9 October 2011. [Online]. Available: http://umm.edu/health/medical/altmed/treatment/biofeedback. [Accessed 23 October 2014].

[5] T. V. Wrigley, M. Simic, M. A. Hunt, R. S. Hinman and K. L. Bennell, "Real-time Movement Biofeedback for Walking Gait Modication in Knee Osteoarthritis," *IEEE,* pp. 132-135, 2009.

[6] J. Sinclair, P. Hingston and M. Masek, "Considerations for the design of exergames," *Association of Computer Machinery,* pp. 289-296, 19 September 2014.

[7] Nintendo, "Wii Balance Board," 2008. [Online]. Available: https://www.nintendo.com/consumer/downloads/wiiBalanceBoard.pdf. [Accessed 13 November 2014].

[8] A&D, "Load Cells Q&A," 2014. [Online]. Available: http://www.aandd.jp/products/weighing/loadcell/introduction/loadcells_qa_04.html. [Accessed 15 October 2014].

[9] A&D, "Definition of the "Load Cell"," 2014. [Online]. Available: http://www.aandd.jp/products/weighing/loadcell/introduction/pdf/1-1.pdf. [Accessed 16 October 2014].

[10] PT Global, "ASB Shearbeam," 2014. [Online]. Available: http://www.ptglobal.com/category/42-asb-shearbeam. [Accessed 17 October 2014].

[11] Analog Devices, "AD7193," 2014. [Online]. Available: http://www.analog.com/static/imported-files/data_sheets/AD7193.pdf. [Accessed 20 October 2014].

[12] Arduino, "Arduino Uno," 2014. [Online]. Available: http://arduino.cc/en/Main/arduinoBoardUno. [Accessed 20 October 2014].

[13] Emant, "Convert an electronic personal weighing scale to measure center of pressure (Posturography)," 2014. [Online]. Available: http://www.emant.com/100001.page. [Accessed 23 October 2014].

[14] G. S. G. M. Makwina, "Inclinometer Based Low-cost Biofeedback Balanceboard for Injury Rehabilitation," *IEEE,* pp. 551 - 556, 2014.

[15] P. Bonato, "Wearable Sensors/Systems and Their Impact On Biomedical Engineering," *IEEE Eng Biol Mag,* no. 22, pp. 18-20, 2003.