WEIGHT MONITORING IN BED USING E-SCALE

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Wheelchair users are more than twice as likely to be obese compared to the general population. This is not surprising considering that it is challenging for wheelchair users to monitor their weight as well as maintain an active lifestyle, both of which are factors that strongly influence a person's ability to manage their weight. The E-scale is a weight monitoring system that was designed for wheelchair users to be able to weigh themselves frequently in their homes. It is comprised of a set of weight sensors that are placed under the legs of a bed or other piece of furniture and passively and continuously measures the weight on each bed leg. This dissertation focuses on the design evolution of the E-scale, and specifically on developing and testing two key aspects of the E-scale that are related to its commercial viability. To make sure that the E-scale can be used in the common scenario where beds are shared by a couple, algorithms for monitoring and differentiating the weight of multiple people using the same bed were developed. To test the usefulness of the E-scale, a weight loss study for wheelchair users was conducted to determine if the E-scale is a feasible technology to use along with a standard behavioral weight loss program adapted specifically for wheelchair users. The results of these two studies as well as a description of future work and preliminary discussions of other applications of the E-scale are reported.

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PREFACE

During the last 7 years, I have had the wonderful opportunity to work at the Human Engineering Research Laboratories (HERL) as a Graduate Student Researcher as I was studying to complete my masters and Ph.D. degrees. The experience has been phenomenal and has given me opportunities to travel and get involved with events and organizations that I never would have imagined before I started my graduate experience there.

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These projects could not have been completed without the help of Anand Mhatre, Beth Casey-Gold and Tricia Karg. Anand designed the first version of the E-scale and continued to assist with the project after he moved to a different project. Beth was the nutritionist for the weight loss study and assisted with the development and execution of the study. Tricia was the clinical coordinator for the weight loss study and pressure injury risk assessment studies and helped a great deal with getting the IRB approval and keeping the consent paperwork in order. Too many interns and co-ops have worked on this project over the last 4 years to mention them all, but I truly appreciate the work that all of them did to assist with the development of the E-scale and the progression of the project. The HERL shop, clinical, and administrative staff are all incredible

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1.0 INTRODUCTION

1.1 WEIGHT ISSUES FOR PEOPLE WITH MOBILITY IMPAIRMENTS

The World Health Organization (WHO) indicates that worldwide obesity has nearly doubled since 1980 and is the fifth leading risk for global deaths [1]. A similar trend has been evident in the United States where the prevalence of obesity for adults has increased from 30.5 % in 1999 to 37.7% in 2014 [2]. The distribution of body mass index (BMI) suggests that 68.8% of adults older than 20 years of age are either overweight or obese [3]. Data show that people with disabilities, specifically those with lower extremity disabilities, are more likely to be obese than the general population [4]. Weil et al. found people with lower extremity disabilities to be two and a half times more likely to be obese than the general population [5]. People with disabilities also have a higher rate of obesity-related chronic conditions such as hypertension, high cholesterol and four times as many have diabetes [6]. Unfortunately, very little attention has been given to a matter of such serious concern [4, 7].

Individuals with lower-limb impairments, specifically wheelchair users, have significantly increased obesity-related health risks [5, 8]. Barriers to exercise and daily activities, accessibility barriers [9], attitudinal barriers towards disability and health [10], psychological decline [8], barriers for maintaining dietary needs over time, and dependence of activity on the type of disability [11] likely contribute to this increased obesity risk. Because of such challenges, loss of

physical capacity [12], depression, fatigue [13], high blood pressure, osteoarthritis, osteoporosis, pressure ulcers and urinary tract infections [14, 15] are common in people with spinal cord injuries who most often use wheelchairs for mobility. Moreover, due to altered body composition of wheelchair users, the increase in percentage of body fat can go unnoticed as their BMI remains in normal range (based on classifications for able-bodied users) [16] which creates risks for diabetes and coronary heart disease [17, 18]. To avoid these risks and preserve physical well-being and independence, weight management is crucial for wheelchair users in addition to increasing activity levels. [19-23].

Maintaining a healthy weight is a challenge for everyone. However, for wheelchair users, there are a host of complex issues that make weight maintenance even more difficult. Physical barriers to exercise and physical activities, attitudinal barriers towards disability and health, environmental barriers for participation, maintaining dietary needs over time, and type of disability are just some of the issues [24, 25]. While engaging in physical activity can be a considerable challenge for this population, the monitoring of daily diet and physical activities, recording physical health and weight conditions, and providing useful feedback are ways to help them start or continue with physical activity [26]. The general population has access to a large and growing number of body monitoring devices ranging from simple pedometers to complex multi-sensor platforms for activity tracking [27]. On the other hand, very few health-monitoring devices are suitable for wheelchair users, and most that are being tailored specifically for wheelchair users are still in a development stage or lack accuracy [27-30].

Studies have shown that regular weight feedback along with a weight loss intervention can lead to better weight loss or better weight maintenance than a weight loss intervention alone [31-33]. In one study, those who self-weighed daily lost 1 BMI unit more than those who self-weighed

weekly and 3 BMI units more than those who never self-weighed [32, 34]. These benefits of self-weighing are generally not available to wheelchair users because commercially available bodyweight scales for wheelchair users are inconvenient for independent use and expensive, making them only feasible for use in a clinical setting. Hospital and clinic-based scales such as roll-on, lift-based and bed scales are available for weight measurement but have little applicability in the home for various reasons. Roll-on scales, for instance, require the person to be weighed with the wheelchair and then transferred out of their wheelchair so that the wheelchair can be weighed separately, which makes assistance necessary. Capacities for most of these scales are limited, which makes them inappropriate for bariatric users in power wheelchairs. Lift-based scales require assistance as well since the user must be transferred onto the lift's platform for weighing. Hospital-based bed scales are convenient for the hospital environment but are not applicable for in-home use as they are expensive for a single user and not designed to provide individual weight measurements when the bed is shared with a partner. These systems also require frequent manual calibration and cannot be integrated with a user's current bed since the instrumentation is custom-fitted to the hospital bed. A few other scales for wheelchair users have been developed in the past several years. One is the Lilypad scale, which is a roll-on scale developed for wheelchair users [35]. It has a capacity of 400 lbs. that makes it only useful for manual wheelchair users and it retails for $628. Another is the Innovision wireless wheelchair scale [36] which has a capacity of 1200 lbs. and retails for $2,295. All of these scales are shown and summarized in Table 1. Most of these scales provide discrete measurements of user's weight that are not recorded or tracked over time. The lack of a self-weighing tool that can be independently used by wheelchair users means that they cannot take advantage of the proven benefit of frequent self-weighing on weight management [33, 37-39]. Without available scales, wheelchair users must estimate their own

weight if they want to keep track, but evidence suggests that their estimates are often incorrect by over 5% [40].

Table 1: Existing weight monitoring technology

Bodyweight scales	Specifications	Capabilities	Shortcomings
 Hill-Rom Bedscale	Capacity: 1,000 lbs; accuracy: 1% of user weight	Battery operated equipment, LCD display	Expensive, large size, stand-alone, needs regular calibration
 Hoyer Presence lift scale	Capacity: 500 lbs; resolution: 0.1 lbs	Recall function for last measurement, battery operated, retrofits to lift	Expensive, change battery, requires assistance
 Befour Roll-on scale	Capacity: 1,000 lbs; resolution: 0.1 lbs; accuracy: ± 0.1 lbs	LCD indicator, Electronic Medical Record (EMR) connectivity via serial output, Wi-Fi, battery operated	Requires assistance for weighing chair, large size for home use
 Lilypad scale	Capacity: 400 lbs; Resolution: 0.5 lbs.	Portable and lightweight, Smartphone/Tablet display Store and graph of weight	Out of business, low capacity makes it only available for use with manual chairs
 Innovision Bed or Wheelchair scale	Capacity 1,200 lbs.; Resolution: 0.5 lbs.	Potable and lightweight, remote display, works with manual wheelchairs or beds	Expensive, does not track or graph weights

One of the consequences of a lack of available in-home bodyweight scales for wheelchair users is a lack of research evidence that evaluates the impact of regular weight monitoring in this population. An article in the American Journal of Preventative Medicine in 2011 titled “Obesity and Disability: Time to Act”, summarizes the complications of the combination of obesity and disability and discusses why this is an important topic that needs to be addressed by researchers [4]. They conclude that: “Reducing obesity among people with disabilities who represent 20% of the population and who experience greater health risks may lower the national prevalence of obesity and lead to improved health and functioning for the group” [4]. It is hypothesized that not having access to regular body weight feedback contributes to the increased prevalence of obesity among wheelchair users. If the general population could not regularly weigh themselves to see if weight loss efforts were having an effect, evidence suggests that fewer people would be successful in changing lifestyle behaviors and there would be even higher numbers of people who are overweight or obese. Since wheelchair users usually only get weighed during physician appointments, and even then, it is not standard practice, their high numbers for obesity could be linked to not being able to regularly monitor their weight. A recent weight loss study for people with mobility impairments specifically stated that the participants not having access to self-weighing technology was a limitation in their study [41]. This need for a simple, in-home weight monitor to assist wheelchair users with maintaining their weight was the motivation that led to the development of the E-scale.

1.2 MARKET NEED AND ANALYSIS

1.2.1 Customer Discovery Process

To better understand the customer profile and value proposition of the E-Scale, a series of 100 interviews with different potential E-Scale stakeholders, including wheelchair users, healthcare providers working in the full gamut of environments (acute-care, inpatient rehab, long-term care, assisted living, and home-health), people working in the weight loss field (personal trainers, weight loss consultants) and other stakeholders potentially involved in the marketing and supplying process of E-scales was performed. This customer discovery process was sponsored through a National Science Foundation (NSF) I-Corps Program and used their well-described methodology [42]. A table identifying the number of people in each group that were interviewed is shown in Table 2.

Table 2: Stakeholder groups interviewed

Group:	N
Wheelchair users	17
Home/telehealth	21
Nursing home	18
Outpatient clinic	9
Vocational Rehab	5
Gym workers	6
Gym goers	14
Acute Care	7
Other	6

Several potential functions of the E-scale were discussed with the stakeholders. Table 3 shows the different market segments that were identified as viable for the E-scale based on feedback from the stakeholders. Since the primary concern and market for this dissertation is the weight monitoring functionality for wheelchair users, a more in-depth overview of the results of the interviews with wheelchair users follows.

Table 3: Market outcomes of I-corps interviews

Customer	**Wheelchairs Users**	**Fitness/Tech Consumers**	**Home Health Agencies**	**Nursing Home Administrators**
Minimum Viable Product	Scale	Passive scale with database	Passive scale with database	Passive scale and alerts with database
Payer	Self and/or Vocational Rehab	Self	Agencies/Ins.	Facility/Ins.
Sales Channel	Web	Web	Tele-monitors/ Medial suppliers	Medical Suppliers
Addressable Market Size	3M (Wheelchairs) 13M (mobility Impaired	40M (activity bands since 2011)	4.7M People 12K agencies	1.4M People 16K agencies
Total Market Value	$3.3B	$10.4B	$1.2B	$700M

The interviewing process for the wheelchair users lasted between 30-60 minutes where the interviewer started by asking open-ended questions related to how they currently get their weight and how important knowing their weight is to them. The interviewer then followed up with some questions specifically about their opinions of how the E-scale currently works and how it was envisioned to work in the future. In all, 17 wheelchair users were interviewed during this process. Their gender and wheelchair type are shown in Table 4.

Table 4: I-corps interviews wheelchair user information

Demographic	Number
Male	11
Female	6
Manual Wheelchair	9
Power Wheelchair	7
Scooter	1

1.2.1.1 Key Insights

Wheelchair users do not typically have a way to weigh themselves in their homes. Of the 17 wheelchair users that were interviewed, 15 did not have a way to weigh themselves at home. The other two found cheap and creative ways to weigh themselves at home. One person bought a large meat scale to weigh himself with their transfer lift as opposed to buying a high cost scale that is made by the lift company. The other person was small in stature and could transfer easily so she bought a regular stand-on scale and put it on a chair and sits on it with her legs off the ground. This confirmed the hypothesis that wheelchair users have a lack of affordable, accessible technology to weigh themselves in their homes.

Wheelchair users are interested in knowing their weight regularly. All but one of the interviewees indicated that they would like to have a way to weigh themselves more often at home. Besides the two people mentioned previously who had the ability to weigh themselves at home, a few other people found alternative ways to weigh themselves. Four of the interviewees work at locations with a roll-on scale so they measure their weight at least once a month at work. One person called nursing homes about using their scales before she found a local drug store that has a chair scale which she now uses. One person weighs herself on a table scale at her veterinarian office when she takes her dog. Most of the other people get weighed regularly when they go to a

doctor's office. The fact that so many of the people that were interviewed found creative ways to weigh themselves demonstrates that they are motivated to know their weight.

Wheelchair users want to track their weight for multiple reasons. Of the 17 people that were interviewed, 6 indicated that they have tried to lose weight previously and would have liked a way to see if they were actually losing weight while dieting. Three people indicated that they are underweight and concerned about losing too much weight. One person said that they use a feeding tube to eat and are never sure if they are using the right amount to maintain weight. The remaining seven people stated that they were interested in maintaining weight.

Wheelchair users are willing to pay for a scale for their homes. Of the 17 people that were interviewed, 12 said they would be willing to pay more than $50 for a scale they could use in their homes while 4 did not give a price. Nine of the 13 who gave a price would pay $100 for the E-scale.

1.2.2 Focus Group

IRB-approved focus groups with Veterans who use wheelchairs were conducted at the 2014 National Veteran Wheelchair Games (NVWG) in Philadelphia, PA to gather qualitative feedback about the E-Scale. A convenience sample of 20 participants who used a wheelchair as their primary means of mobility, were 18 years of age or older, and were able to speak and understand English were recruited and consented. A pre-study survey was administered to collect demographic information and types and satisfaction with the assistive technology (AT) that they were currently using. Version 1 of the E-Scale was demonstrated by a single moderator (See Chapter 2 for different E-Scale versions). Current methods of weighing for wheelchair users were also explained. The E-Scale was presented as a scale for home-use and functionality of the prototype

was demonstrated to the participants. Feedback regarding the user's weight measurement practices, preferred weight scales, and views on AT and the E-Scale's in-home usability were obtained using a post-study questionnaire. Participants were asked to rank lift-based scales, the E-Scale and roll-on scales based on preference and a Kruskal-Wallis test was used to test the significance between preference for the three scales at a $p=0.05$ level of significance. Subjects were asked about their opinions on the design, data display, smart phone app usage, information sharing concerns using the app, and pricing during an open-ended discussion that was audio-recorded. The need for E-Scale-like technology was evaluated based on the percentage of participants facing frustrations with current scales and the percentage of participants who wished to use the E-Scale.

Six focus groups were conducted at the NVWG with a total of 20 Veterans – 17 males and 3 females. Table 5 shows participants' characteristics including type of disability and assistive device used for mobility needs. Regarding their views on AT, participants answered safety as their primary factor when deciding on AT with usability (95%), device cost (90%), and attractiveness (90%) as other important factors for consideration. Two participants owned lift-based scales at home.

Table 5: Disability and AT data for NVWG focus group participants

Average length of injury	19 years
Number of people with	
Spinal Cord Injury (SCI)	10
MS	2
Stroke	1
Number of wheelchair (WC) users	
Manual Wheelchair (MWC)	12
Power Wheelchair (PWC)	7
Scooter	1

Out of 20 participants, 11 described difficulty in maintaining weight, 17 visited their doctor monthly to get their bodyweight and 15 (75%) preferred to weigh more often than they currently did. Table 6 shows the general feedback for the E-Scale. About 80% of participants stated that they would like to use the E-Scale. When the participants were asked about their preference for weighing equipment, the E-Scale was significantly preferred over lift-based scales and roll-on scales ($H=20.75$, $df = 2$, $p<0.0001$). Ninety percent (90%) of the subjects indicated that they would be comfortable if the E-Scale app shared their weight with their doctor and 60% said they would share their information publicly to help motivate their weight loss through social competitions (e.g. gamifying). Fourteen participants were willing to pay, on average, $400 as an out-of-pocket expense for the E-Scale and said they would like to buy the E-Scale if it became available at the stated price. Certain themes were notable during the focus group discussions. Most participants thought the opportunity of getting weighed daily in their home would be very helpful for weight management. With regards to accessing weight data, availability of an LCD screen and smartphone app for instant data display were appealing to the participants. Only one participant indicated that they would not choose to use the app due to privacy concerns. All participants appreciated the visual aesthetics (attractiveness) of the E-Scale but two of them were not satisfied with wires underneath the bed and size of the load cells; they preferred it to be more compact.

Table 6: Overall feedback about E-scale provided by NVWG focus groups

Statements for overall E-scale Feedback	Disagree	Neutral	Agree
I would choose to use the E-scale	15%	5%	80%
Using the E-scale would make my life easier	20%	15%	65%
I would be anxious about using the E-scale	55%	5%	40%
It would be embarrassing to be seen using the E-scale	95%	0%	5%
Using the E-scale would be an invasion of my privacy	85%	5%	10%
It would be easier to get another person to help rather than use the E-scale (accessibility)	95%	0%	5%
It is important that we develop a E-scale that can do this	15%	5%	80%
The government should invest resources to develop the E-scale	20%	10%	70%

Overall, the focus groups and interviews demonstrated that there is a desire for wheelchair users to be able to track their weight easily and affordably in their homes, and that the E-Scale was an attractive solution. Besides weight monitoring, the interviews and focus group results suggested that the E-scale may be useful for providing information about other indicators that are relevant for individuals in bed, including measuring sleep quality, predicting bed exits, monitoring pressure injury risk (associated with lack of repositioning), and compliance with turning protocols in nursing home facilities. Several nursing home administrators, for instance, volunteered their facilities to conduct pilot studies.

1.3 DISSERTATION OVERVIEW

This dissertation was motivated by the results of the customer discovery process and includes a broad range of activities. First, Chapter 2 describes the design evolution of the E-Scale, including the design and testing outcomes for four different versions of the E-scale. This chapter includes the design specifications, testing processes and reasons for continued iterations. Chapter 3 describes the develop algorithms to be able to differentiate between two people sharing a bed so that both can be passively weighed with the E-scale. Chapter 4 describes a weight loss intervention pilot study that tested the feasibility of the E-Scale in providing daily weight feedback to wheelchair users. Chapter 5 describes potential areas of future work with the E-Scale and includes results from a pilot study investigating whether the E-Scale can provide insight into pressure injury risk. Table 7 shows how each of these chapters fits into a technology readiness level chart for the E-Scale which was developed by NASA and is meant to outline the sequential process to move a technology into commercial production [43].

Table 7: E-scale functions and technology readiness

TECHNOLOGY READINESS LEVEL:	Ideation	Research	Proof of Concept	Prototype	Pre-Production	Mass Produced	Commercialized
Core Technology							
C1: Hardware (Sensors)	Ch. 2				Ch. 4		
C2: Software (E-Scale Data Collection)	Ch. 2				Ch. 3,4,5		
Data Analysis Modules							
M1: Weight Feedback	Ch. 2				Ch. 3,4		
M2: Multi-person Decoding	Ch. 3				Future work		
M3: Pressure Injury Risk	Ch. 5				Future work		
M4: Sleep Quality	Future work						
M5: Predictive Bed Exit (fall risk)	Future work						

1.4 SPECIFIC AIMS

These specific aims are related to the two human subject studies that are described in Chapters 3 and Chapter 4. Because the E-Scale is meant to be used in the home environment where pets, children, and couples often use a single bed, a predictable challenge is being able to classify who is on the bed so the measured weights can be assigned to a target person. Chapter 3 is focused on developing a data classifier to address this challenge. The feasibility of the E-Scale to provide weight feedback during a weight loss intervention for wheelchair users was then tested. The goal of the study, which is described in Chapter 4, was to investigate the accuracy and precision as well as the usability of the E-scale in the field during a standard behavioral weight loss intervention. The research questions, aims and hypothesis for these two studies are as follows:

Research Question 1: Can the E-scale track the weight of two people (i.e. a couple) who share the same bed?

Aim 1: To develop algorithms for automatically determining which of two people entered or exited a bed to determine which person a weight measurement should be assigned to.

Hypothesis 1: The E-scale can differentiate the weight measurements of two people based on the magnitude of the weight change measured during an event (i.e. large weight change) and the side of the bed that has the larger weight change with greater than 85% accuracy.

Research Question 2: Will the E-scale be a useful, feasible and effective tool to assist a weight-loss intervention for wheelchair users?

Aim 2. To investigate the usefulness and feasibility of the E-scale system, and effectiveness of the E-scale coupled with a behavioral weight-loss intervention to provide the capability for daily weighing related to food intake and related behaviors.

Hypothesis 2a: The E-scale will be useful based on self-reported feedback from wheelchair users by being easy to use, being their preferred weight monitoring system, and by their feeling that they would use the E-scale if it was available for them to purchase.

Hypothesis 2b: The E-scale will be feasible by providing accurate (+/- 2 lbs. from a calibrated scale measurement) and repeatable (< 2 lbs. difference from day-to-day) weight measurements and by the wheelchair users continuing to use the E-scale more than 70 % of the days of the study.

Hypothesis 2c: The E-scale coupled with the weight loss intervention will be demonstrated to be effective by wheelchair users by them achieving significant decreases in weight, abdominal girth, and body fat percentage.

2.0 E-SCALE DESIGN AND ITERATIONS

The E-scale design team at the university implemented a systematic product design procedure proposed by Ulrich and Eppinger [44]. Throughout the process, a standard product development process, which is shown in Figure 1 [44], was followed. Prior to building Version 1, the first three steps in the processes were completed. The different versions of the E-scale are all part of the iterative cycle of "design, build, test". Versions 1, 2, and 4 were designed and built by the design team at the university. Version 3 was designed and built by a start-up company named Nexaware, which was launched by an external team (non-Pitt) to bring the E-scale to market.

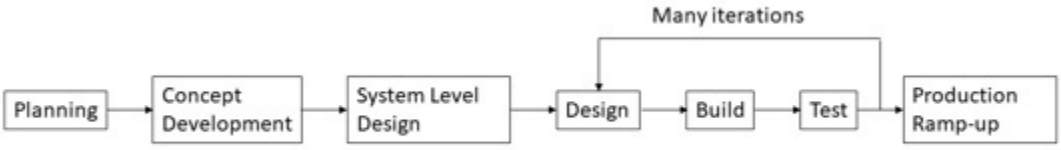


Figure 1: Product development process

The design goals included the following:

(1) Weight measurement should be collected and available to the user on at least a daily basis to maximize the impact it can have on weight management [45, 46].

(2) The system should allow wheelchair users to record their weight independently without the need for any additional assistance.

Based on these design goals, a core set of design requirements were developed, and possible design concepts were brainstormed within the design team. The discussion was focused

on integrating the weight-measuring process in daily activities such as bathing, toileting or resting. Of the possible design and integration options, a furniture-based approach of integrating weight monitoring equipment with a user's bed was selected for feasibility and convenience.

2.1 DESIGN SPECIFICATIONS

A search of hospital bed-based weighing systems, roll-on, lift-based, and wheelchair scales was performed through the internet and digital product catalogs as a means of benchmarking the E-scale capabilities. Table 8 lists these scales along with their respective specifications and features that were considered. The following design specifications were established through benchmarking:

1. Performance: Current wheelchair scales lack usability in homes but performance of these scales is appropriate, which should be replicated with below specifications.
    - Capacity: 1200 lbs.; the E-Scale has 200 lbs. more than benchmarked bed scales to accommodate for the weight of a bed partner.
    - Accuracy = 1.0 lbs.; benchmarked against other scales.
    - Resolution = 0.5 lbs.; benchmarked against other scales.
    - Precision = ±1.0 lbs.; benchmarked against other scales.
2. Accessibility: Available for home use to the wheelchair user without additional assistance.
3. Automated operation: Provide automatic zeroing and not require calibration.
4. Installation: A user who is non-technical should be able to setup the E-Scale.
5. Data access: Easy and immediate access to weight data and user weight history.
6. Attractiveness: The E-Scale should look attractive for use in the home with the bed.
7. Cost: The E-scale should retail for less than $200 based on market analysis in Chapter 1.

Table 8: Wheelchair scales for benchmarking

Bodyweight scales	**Specifications**	**Capabilities**	**Shortcomings**
Hill-Rom Bedscale	Capacity: 1,000 lbs. Accuracy: 1% of user weight Resolution: not specified	Battery operated equipment, LCD display	High cost, large size, stand-alone, needs regular calibration
Stryker Bedscale	Capacity: 500 lbs. Accuracy: not specified Resolution: not specified	One-touch LCD scale allows accurate, repeatable readings	Large size, stand-alone, needs calibration
Hoyer Presence lift scale	Capacity: 500 lbs. Accuracy: not specified Resolution: 0.1 lbs.	Recall function for last measurement, battery operated, retrofits to lift	Expensive, change battery, inaccessible
Invacare Reliant 600 Power Lift	Capacity: 600 lbs. Accuracy: not specified Resolution: not specified	Power lift, battery operated, audible low battery alarm	Change battery, inaccessible, expensive
Befour Roll-on scale	Capacity: 1,000 lbs. Accuracy: +/- 0.1 lbs. Resolution: 0.1 lbs.	LCD indicator, Electronic Medical Record (EMR) connectivity via serial output, Wi-Fi, battery operated	Requires assistance for weighing chair, large size for home use
Detecto 495 Roll-on scale	Capacity: 400 lbs. Accuracy: not specified Resolution: 0.25 lbs.	Mechanical weighing scale, one-side ramp	Stand-alone, requires assistance for weighing chair
Lilypad scale	Capacity: 400 lbs. Accuracy: not specified Resolution: 0.5 lbs.	Portable and lightweight, Smartphone/Tablet display Store and graph of weight	Out of business, low capacity makes it only available for use with manual chairs
Innovision Bed or Wheelchair scale	Capacity: 1,200 lbs. Accuracy: not specified Resolution: 0.5 lbs.	Potable and lightweight, remote display, works with manual wheelchairs or beds	Expensive, doesn't track or graph weights

2.2 VERSION 1

2.2.1 Design Description

2.2.1.1 Initial Prototyping

The design team experimented with off-the-shelf load cells for force measurements that did not meet the above specifications, and consequently a fully-customized sensing configuration was built on a breadboard. This configuration consisted of strain gauges from Vishay Precision Group (Malvern, PA) soldered to form a full Wheatstone bridge with two gauges bonded on each longitudinal face of the cantilever beam. The resulting voltage difference across the bridge is measured by an Arduino microcontroller after signal amplification through an INA125P amplifier (Texas Instruments, Dallas, TX). Prototyping the bedside controller unit included wiring a Liquid Crystal Display (LCD) array and SD card module to the microcontroller. A smart-phone prototype app was developed in Android Studio (Google Inc., Mountain View, CA) for data display and weight tracking that connects with the controller unit via Bluetooth.

2.2.1.2 Load Cell Design

Following successful breadboard prototyping, the instrumented components were incorporated into a custom-made prototyping circuit board (PCB) housed within the load cell case (Figure 2). The PCB was designed with Altium software (Altium Limited, Carlsbad, CA) and fabricated. The load cell housing components (Figure 3) were 3D printed using a Fortus 400mc, a Fused Deposition Modeling machine (Stratasys, Eden Prairie, MN), with Acrylonitrile Butadiene Styrene (ABS) plastic. A concave-shaped top of the load cell housing was created to support a variety of bed feet. It pockets an engraved rubber disc that allows the user to position the bed feet coaxially

to minimize any off-centered loading. A sensor button is screwed to the top piece and the other side holds a hard-pressed steel ball that presses against the cantilever beam for a single-point contact. A rubber diaphragm sits between the case top and pressing button to attempt to form a centrally located, single point force transmission to the load cell. The diaphragm is secured on the circumference of the sensor base by an aluminum ring and screws. The sensor base contains a pocket for a mounting tray containing the load cell assembly and an outlet for the USB connector. Desiccant bags are placed in the load cell housing to prevent moisture from affecting the components. Each load cell is 5 inches in diameter and 1 ¼ inches thick.

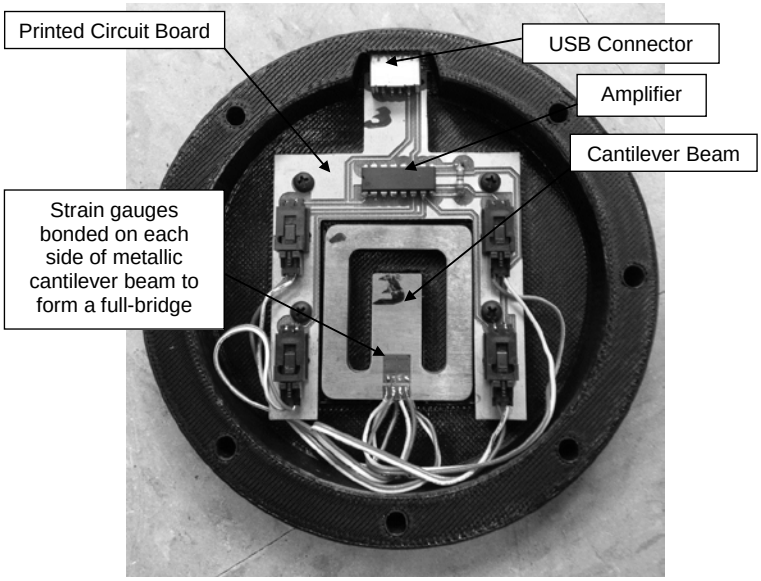


Figure 2: Electromechanical assembly of the load cell

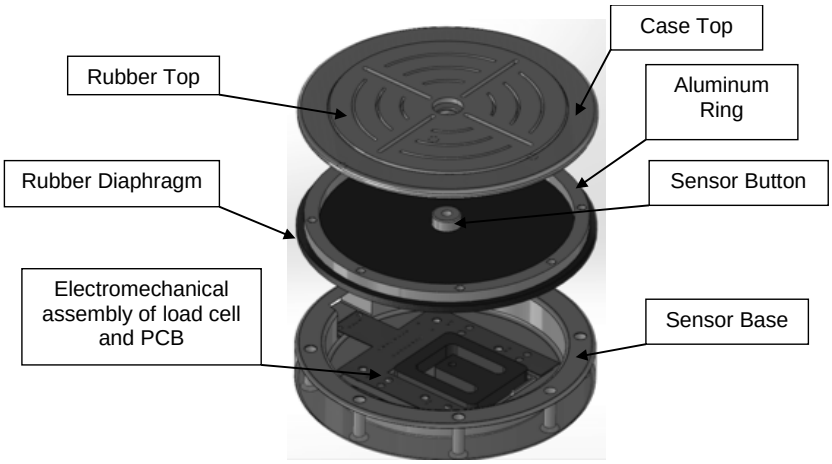


Figure 3: Load cell case components

2.2.1.3 Bedside Controller Unit Design

The bedside controller unit (Figure 4) houses the microcontroller and other peripheral components. The unit is wall-powered and looks similar to a digital alarm clock with an LCD display. The controller connects with all load cells serially. The controller converts the voltage data sampled every second from each load cell and converts the resultant into a weight format for display. An SD card is used for storing data on the controller, and Bluetooth is used to send data to a smartphone app (Figure 5) using a Bluetooth modem - BlueSMiRF Silver. The E-scale is calibrated as part of the installation procedure, and subsequently is able zero (‘tare’) itself with the press of a button on the bedside display to account for environmental changes, such as a pillow or different comforter being added to or removed from the bed.

Figure 4: E-Scale system - four load cells and the bedside controller unit.

Figure 5: E-Scale app main screen (left), graphical display (center), and profile page (right)

2.2.2 In-Lab Testing

After successful prototyping, a full-scale model of the E-Scale with four load cells and a controller unit was developed, fabricated, and tested in the laboratory. The model was tested in laboratory settings using test cases to assess performance specifications along with other essential scale characteristics adapted from ASTM International standard E898-88: Standard Test Method of Testing Top-Loading, Direct-Reading Laboratory Scales and Balances [47]. These test cases are listed in Table 9. For testing, weights of known masses and a 185-lb extrication 'Survivor' dummy (Dummies Unlimited, Pomona, CA) were used. All test cases in Table 9 except Case 1 were tested with the E-Scale installed under a mat table.

Table 9: Test cases used for the preliminary testing of E-scale

Test Parameter	Test Case
1. Capacity	Load each load cell with a static load of 300 pounds using a Material Testing System (MTS, Eden Prairie, MN) and verify if the voltage output is within the range to be measured
2. Accuracy	Turn ON the E-scale and zero the weight. Without loading, record weight after 30 seconds. Increment the load by 10 pounds every minute and record the weight subsequently after 30 seconds of loading. Graph weight readings against true weights and calculate accuracy.
3. Precision	Place a dummy on the E-scale five times and record the readings subsequently after 30 seconds of loading to verify repeatability. Allow 5 minutes between each loading.
4. Hysteresis	Without loading, record weight after 30 seconds. Increment the load by approximately 10 pounds every minute and record weight subsequently after 30 seconds of loading. Once capacity is reached, unload the E-scale every minute in the reverse order and record the weight after 30 seconds of unloading until the E-scale is completely unloaded.
5. Drift	Place a dummy on the bed and check the drift from the dummy's weight over 24 hours
6. Creep	Remove the dummy from the table after Drift testing and record weight measured by the E-scale.

Capacity testing of each load cell was performed using a servo-hydraulic force testing system (MTS, Eden Prairie, MN) over a static load range of 11 lbs. (5 kg) to 300 lbs. (136 kg) and load cell behavior (linear or non-linear) was characterized. The test yielded linear response as seen in Figure 6 with each load cell measuring at least 300 lbs. (136 kg). For the accuracy measurement test (Figure 7), weights of approximately 10 lbs. were selected and were measured on a calibrated weight scale for obtaining accurate weights. Twenty-five weight plates were available for testing with a total load of 260 lbs. Weights were added to the E-Scale, which was installed under the mat table, and weight measurements were taken successively after each loading. The reported accuracy is the difference between observed weight and actual weight at 260 lbs. (almost one-fourth of the scale capacity). For the precision test (Figure 8), the mat table was loaded with a 185-lb. dummy

5 times and weight measurements were obtained. The precision calculated is the standard deviation of the weights. Table 10 displays the bench testing results.

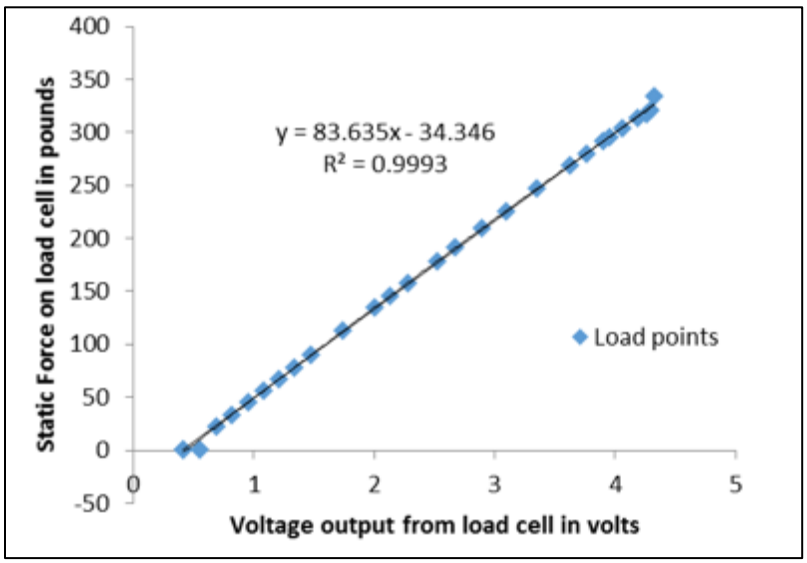


Figure 6: Static force versus output voltage characteristics for a load cell

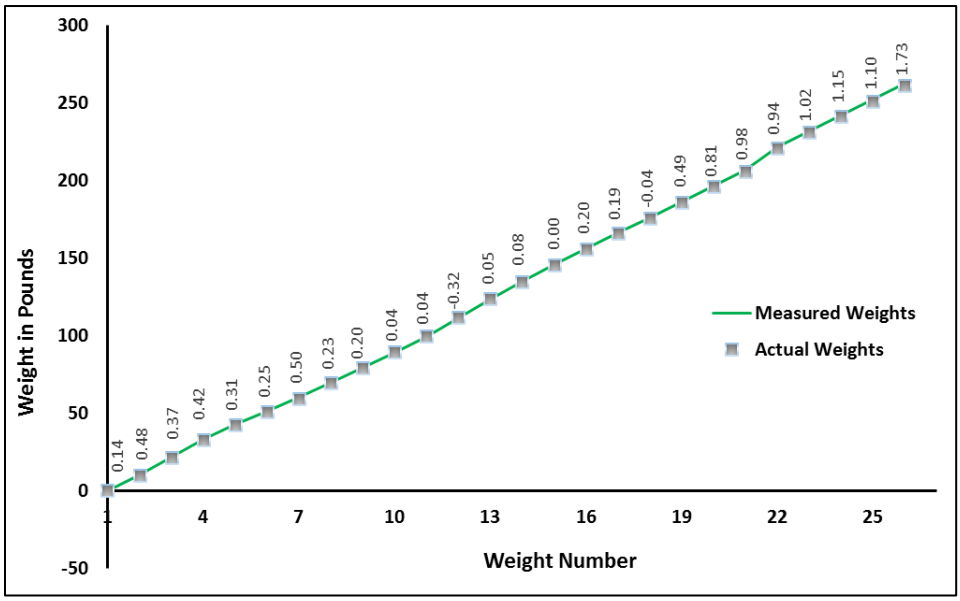


Figure 7: Load data in accuracy testing (difference between actual and measured weights shown as data labels on the graph line)

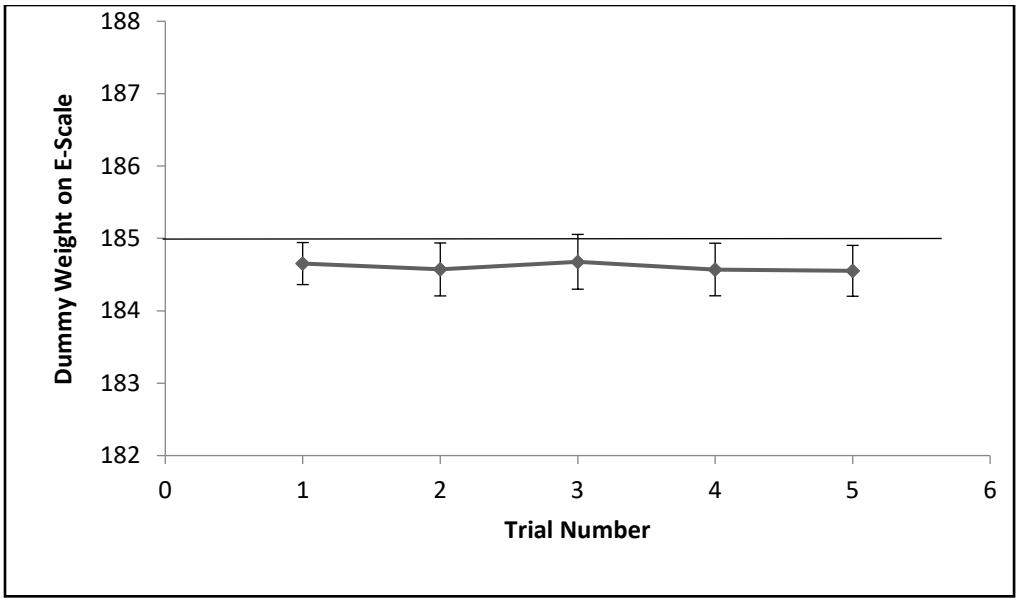


Figure 8: Means and standard deviations of dummy trials used to estimate the E-Scale precision.

Table 10: E-scale Version 1 performance

Test parameters	Target Value	E-scale performance	Target achieved
Capacity	1,200 lbs.	1,200 lbs. (not tested beyond limit)	✓
Accuracy	1.0 lbs.	1.73 lbs.	×
Precision	±1.0 lbs.	± 0.35 lbs.	✓
Resolution	0.5 lbs.	0.5 lbs.	✓
Hysteresis	No target	0.5 %	NA
Drift	No target	0.58 lbs.	NA
Creep	No target	0.71 lbs.	NA

2.2.3 Community Testing

This version of the E-scale was initially tested in homes of the investigators and with the couple study described in Chapter 3. After 3 subjects had participated in the study, it was noticed that the weight was not as accurate as it was in the lab and was varying greatly when the bed leg would move on the top of the E-scale sensors.

2.2.4 Design Deficiencies

After testing Version 1 of the E-scale in the lab and in the homes of investigators, field-based trials in the community with people in their homes began. It was soon realized that there was an issue with the E-scales not reading consistently and repeatably if the bed leg shifted from the center of the E-scales. Although the original design had a diaphragm to try to maintain the weight going through the load cell even if the weight was slightly off-center, it was soon discovered that it was not working as intended. Experiments with other diaphragm materials and thicknesses were conducted, but they did not achieve satisfactory results with maintaining equal weight when the placement of the mass was moved on the top of the E-scales. This led to the design changes in described in Version 2.

2.3 VERSION 2

2.3.1 Design Description

Version 2 consists of three load cells positioned around the perimeter of the E-scale sensor equally spaced at 120^{o} (Figure 9). As long as the center of mass of the bed leg is positioned within the inscribed circle connecting the three load points on the load cells, all of the weight was transferred to the load cells. The voltage from the three sets of strain gauges is recorded in series so the weight of the three load cells is summed. This version was also fabricated in the university machine shop with the load cells being cut out on a water jet and the plastic components being 3-D printed.

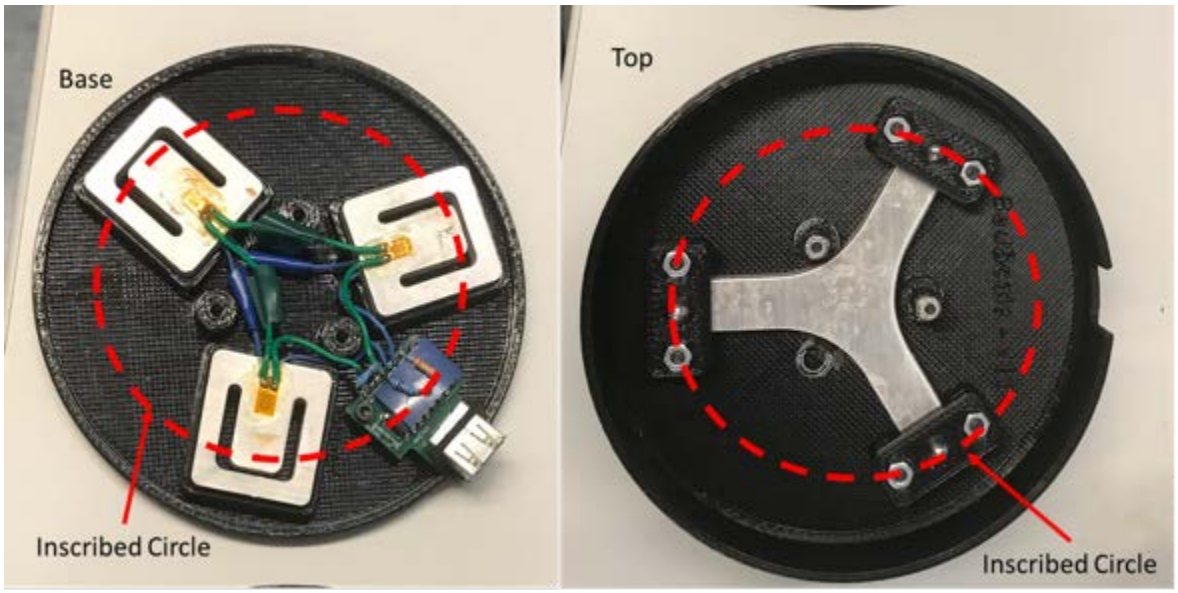


Figure 9: Version 2 of E-scale to account for off-center loading

2.3.2 In-Lab Testing

Because the differences between Version 1 and this version solely had to do with accuracy issues when off-center loads were applied, a full-scale testing procedure was not performed like the one conducted with Version 1. The strain gauges and load cells in this version were identical to the ones used in Version 1 so their behavior was identical. The accuracy and precision of this version was tested in the lab with the weight at the center of the E-scales and the results were found to be similar to Version 1. When weight was placed slightly off-center though the accuracy of this version remained consistent and did not decline as was the case with Version 1. Table 11 shows the performance characteristics of Version 2

Table 11: E-scale Version 2 performance

Test parameters	Target Value	E-scale performance	Target achieved
Capacity	1,200 lbs.	1,200 lbs. (not tested beyond limit)	✓
Accuracy	1.0 lbs.	Similar to Version 1 (1.7 lbs.)	×
Precision	±1.0 lbs.	Similar to Version 1 (±.35 lbs.)	✓
Resolution	0.5 lbs.	0.5 lbs.	✓
Hysteresis	No target	Similar to Version 1 (0.5 %)	NA
Drift	No target	Similar to Version 1 (0.58 lbs.)	NA
Creep	No target	Similar to Version 1 (0.71 lbs.)	NA

2.3.3 Community Testing

Version 2 of the E-scale was used for the couple study that is described in Chapter 3. Based on data observation, it was determined that the repeatability and consistency of this version of the E-scale in the community setting was superior to Version 1.

2.3.4 Design Deficiencies

During the community testing, an accuracy issue related to carpet was discovered with this version. Since the top of the E-scale cases overlapped the bottom and hung down on the side of the bottom part, the top would come into contact with carpet and some of the weight would be transferred directly to the carpet rather than going through the load cells. At this point, the E-scale technology was licensed to Nexaware and design for manufacturability also was identified as a deficiency of the system. These issues were conveyed to Nexaware during the licensing process.

2.4 VERSION 3

2.4.1 Design Description

The E-scale technology was licensed to a startup company called Nexaware, which was created to bring the E-scale technology to market. Nexaware's go-to-market strategy focused on the healthcare market, not the wheelchair user market, and consequently the design goals shifted to developing a wireless communication system and sensors which would accommodate beds with wheels that are commonly used in nursing homes and other healthcare facilities. Nexaware also applied design for manufacturing (DFM) principles to prepare for large-scale production and make the software more adaptable for multiple analysis techniques. The license to Nexaware included Version 1 and 2 designs and the lab-based and community-based results of these versions as they were being collected, but the team at Pitt was not included in any decision making regarding Nexaware's design. Images of Nexaware's design (Version 3) are shown in Figure 10.

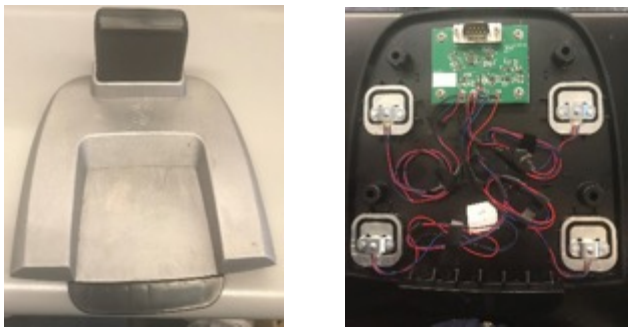


Figure 10: Photos of Version 3 of E-scales

Version 3 of the E-scale consists of 4 load cells, which are positioned close to the corners of the weighing pad. Each E-scale has a battery pack that has 3 AA batteries in series to supply

approximately 4.5 Volts to the E-scale. The voltages from the strain gauges are collected in series so that they are summed to a total voltage. The analog voltage is acquired by a PCB board in the E-scale and then converted to a digital hex value that is communicated via Bluetooth to a Raspberry Pi computer. The Raspberry Pi computer collects the hex values from the 4 individual E-scales and converts them to weights. It then subtracts a "zero" weight (weight from each E-scale when the bed is empty) and sums them for the total weight to be measured. Nexaware's intent was for the Raspberry Pi to then send each total weight value (recorded approximately every 2 seconds) via Wi-Fi to an Amazon Web Server (AWS) database to be stored. The user would then be able to use an android tablet to view their current weight from the database. A picture of the entire setup is shown in Figure 11.

Figure 11: Version 3 full system

Nexaware hired consultant companies to design the hardware and software separately. The hardware designs were completed by Spark Product Development, LLC

(sparkproductdevelopment.com). The AWS database was designed by Veracity Consulting (veracity-consulting.com) and the Android app was developed by Kova Digital (kovadigital.com). An engineer internal to Nexaware designed the software on the Respberry Pi computer and the calibration software. The hardware was designed and fabricated, but the complete functionality of the software communication between the app, Raspberry Pi computer and AWS database was never completed, which led to our research team developing a local approach to collecting data. A local database on the Raspberry Pi to store the data locally was developed and a Bluetooth app that communicates directly with the Raspberry Pi to stream the weight measurements to a tablet was designed. This in essence became a wireless screen for the E-scale. A screenshot is shown in Figure 12.

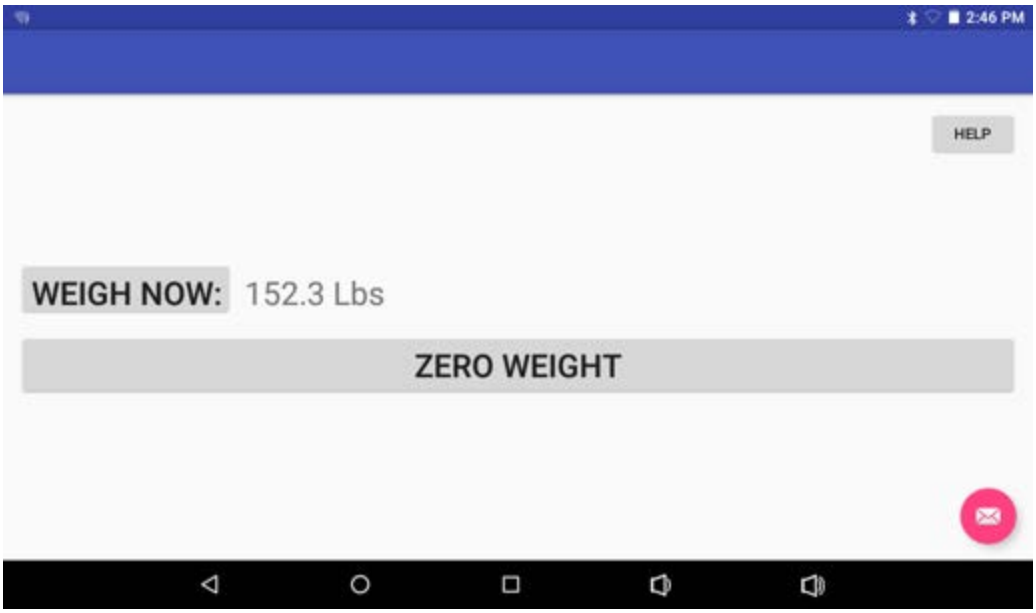


Figure 12: Screenshot of Version 3 E-scale app

2.4.2 In-Lab Testing

After the first E-scale system was delivered for demonstration and testing, a series of in-lab tests were performed followed by design modifications. These modifications were performed by the team at Pitt and are described in detail below in the design deficiencies section 2.4.4 and were communicated to Nexaware. The accuracy of the weight and the consistency of the weight measurements when the weight was shifted on the bed or on the E-scales was tested. It was determined that the accuracy when the weight was not shifted met our design spec, but that accuracy dropped off when the weight was shifted on the bed or on the E-scales.

Creep was tested by placing a 185-lb dummy on a mat table with the E-scale underneath and observing the weight change after 24 hours. Drift was also tested by removing the dummy and observing the weight of the empty mat table. Both were less than 0.5 lbs. which met specification.

After the local database was developed and functional, the capability of the system to function for the three-month weight loss study in Chapter 4 was tested. The database was artificially filled with 10 million data points (about 6 months of data) and the E-scale was left to run for 24 hours to make sure that the functionality of the E-scale would not be affected by the database memory consumption. This test showed that the E-scale would still be functional after 6 months of data collection. The 10 million data points accounted for approximately 2.5 GB of memory on the Raspberry Pi which was less than 25% of the available memory.

The Bluetooth app was tested under normal operation situations including: changing view from portrait to landscape, allowing the tablet to go to sleep, and closing and reopening the app. The app remained functional under all of these situations.

When the E-scales were calibrated, two known weights were placed on each E-scale and it was calibrated to those weights. The E-scale was then unloaded and loaded again with the same

weights. The E-scale was calibrated sufficiently if the weight from the E-scale was within 1 lb. of the known weights on the E-scale and if the weight from the unloaded E-scale was within +/- 0.5 lbs. Table 12 shows the performance of Version 3 of the E-scale.

Table 12: Version 3 performance

Test parameters	**Target Value**	**E-scale performance**	**Target achieved**
Capacity	1,200 lbs.	1,200 lbs. (not tested beyond limit)	✓
Accuracy	1.0 lbs.	<1.0 lb. from known weights during calibration	✓
Precision	±1.0 lbs.	Not tested	×
Resolution	0.5 lbs.	0.1 lbs.	✓
Hysteresis	No target	Not tested	NA
Drift	No target	<0.5 lbs.	NA
Creep	No target	<0.5 lbs.	NA

2.4.3 Community Testing

Version 3 of the E-scale was used in the weight loss study described in Chapter 4. Nine of these systems were placed in wheelchair users' homes and they were asked to use them every day for the duration of the three-month study. Details of the performance of Version 3 in this study is included in the discussion of Chapter 4.

2.4.4 Design Deficiencies

Several issues with Version 3 were identified throughout the in-lab testing and community testing that are described below. The five main issues that were identified include: the battery pack did not fit well into the slot on the top, the solder joints for the battery packs were weak, the plastic

base deformed when loaded on a soft surface (e.g. carpet) leading to a reduction in accuracy and precision, the Bluetooth connection was inconsistent, and the placement of the person's weight on the bed or placement of the bed leg on the E-scales caused changes in the measured weight. More detailed descriptions of the issues and solutions follow.

2.4.4.1 Battery Pack Fit

The battery packs were designed to be plugged into the E-scales as shown in Figure 13. However, the injection molding process for the battery pack cases and casting process for the aluminum tops resulted in a tight fit. The battery packs had to be forced into the slots which caused two issues. First, the battery pack caused an initial load on the E-scale since the friction of the connection pressed the aluminum top onto the load cells. This caused errors with the calibration, since the calibration process is conducted without the battery pack in place, and ultimately the accuracy. Second, after repeated loading and unloading, the battery pack would become disconnected from the PCB board in the E-scale which would cause the system to stop working.

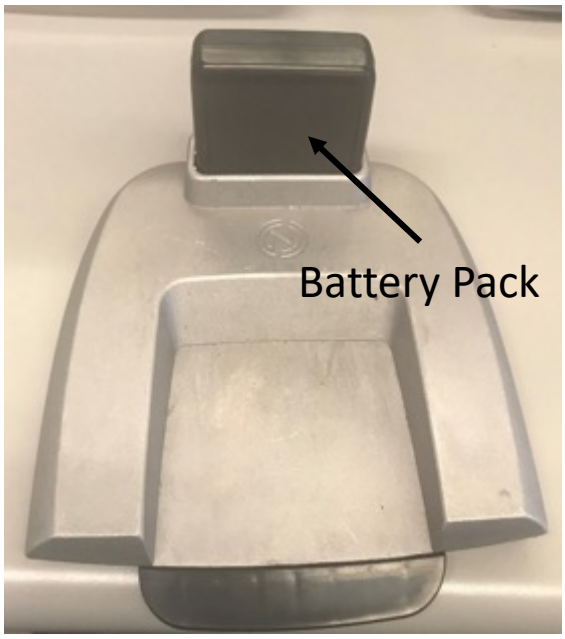


Figure 13: Image of Version 3 E-scale with battery pack

To remedy this situation, a CNC milling operation was programmed and a jig was developed to expand the opening of the aluminum housing so that the battery pack and aluminum would not contact. The original intent for a tight fit was to make the E-scale water resistant so that a spill on the E-scale would not damage the PCB board which is under the battery pack in the E-scale. This could still be accomplished in the future by adapting the mold for the battery packs to have a ridge that covers the slight gap between the battery pack and the aluminum top or by adding a rubber skirt around the battery pack. Other alternative designs could also place the battery packs at a different location. This design deficiency was identified and resolved before the weight loss study began so it did not affect the study data described in Chapter 4.

2.4.4.2 Weak Solder Joints in the Battery Pack

The original solder joints in the battery packs were very poor so they were routinely breaking with general use. It appeared that the original soldering was done cold and the solder did not fully

connect to the pins. This caused the E-Scales to become disconnected and the system to stop working. In some cases, it also drained the batteries very quickly.

This deficiency could be easily resolved by re-soldering the joints. However, it was not discovered until a few weeks into the weight loss study so some of the connection issues and missed measurements during the beginning of the study may have been due to this issue.

2.4.4.3 Base Deformation

The plastic base which houses the load cells is flexible which caused it to deform when the E-scale was loaded while on a soft surface such as carpet. In cases of high loading (e.g. a heavy bed and/or multiple people on the bed), the base would deform and make contact with the edges of the aluminum top which caused load to be transferred through the case rather than through the load cells. This caused a significant reduction in accuracy, especially on soft surfaces like high pile carpet.

As a first step to address this deficiency, pieces of medium density fiberboard (MDF) were placed under the E-scales to serve as a stiffer surface. This improved the accuracy but did not completely resolve the deficiency because the MDF also can deform under high loads. The final step which resolved the deficiency was to space the plastic base further apart from the aluminum top through the use of larger internal spacers. A picture of an E-scale before and after this change was made is shown in Figure 14.

Figure 14: Expanded gap with taller spacers

This took some time as it required some machining to make the taller spacers and purchasing of longer shoulder bolts to connect the base to the top. This allowed the plastic base to still be deformed when loaded, yet not make contact with the aluminum top so that no weight could be transferred through the case. In future designs, the E-scales could use these taller spacers, use an aluminum base and/or offset the base and top so that the edges are not vertically aligned.

It was noticed during and soon after installation of the E-scales for the weight loss study that the weight being reported by the E-Scale was lower than expected for several participants. However, it took a few weeks to identify the cause of the low weights and still more time to resolve the deficiency. By the end of the study, only 4 of participants' E-scales were able to be modified, but the ones that were modified saw the accuracy of the E-scales significantly increased.

2.4.4.4 Inconsistent Bluetooth Connections

The 4 individual E-Scales connect to the Raspberry Pi computer through 4 Bluetooth connections where the computer acts as a client and receives the data from the 4 E-scales. The Android tablet then connects to the Raspberry Pi to receive the total weight calculated from the 4 E-scales for the user to view. This requires the Raspberry Pi computer to act as a server as it is sending the signal to the tablet. It appears that this setup, which requires the computer to be both a Bluetooth client

and server, caused many errors with maintaining the connections with all of the E-scales and the tablet.

A full solution for this issue was never identified and tested. In the future, the E-scale software should be redesigned to allow for a more consistent user interface to the E-scale system. It may be that some further refinement of the current Bluetooth setup or using additional Bluetooth libraries on the computer could maintain the connections better. Alternative solutions could be to use a WIFI connection to view the weight from the computer or to use a hardwired LCD or other display which does not require wireless data transmission for the user to see their weight.

This issue led to problems throughout the weight loss study as the tablet connections were routinely lost which left the participant without a way to view their weight. Sometimes restarting the Bluetooth app, tablet, and/or the Raspberry Pi computer would fix the connection, but in most cases, a time had to be scheduled with the participant to go to their homes to investigate the issue. This had a significant impact on the numbers for compliance with the weighing protocol as there were stretches (days or weeks) where the participant's E-scale was not working.

2.4.4.5 Weight Placement

For a 4-scale E-scale system (standard 4 leg bed), there are a total of 16 load cells which collectively add up to measure the total weight of the system; 4 E-scales with 4 load cells in each E-scale. The 4 load cells in each E-scale are inherently assumed to behave identically as they are connected in series and only the total summed voltage is measured. This can never be perfectly true so the placement of the leg of the bed on the individual E-scale will change the weight measured by the E-scale depending on the relative weight distribution on the 4 load cells. Therefore, if the bed legs slide or are shifted on the E-scales, it can cause errors in the weight measured by the E-scales.

The 4 E-scales are then calibrated individually. In testing, the E-scales were calibrated using known weights of 52 and 96 lbs. Even with the E-scales being calibrated, they did not behave identically so a shift in the position of the person's center of mass on the bed, could cause the measured weight to vary. Meaning that if a person moved (rolled or shifted) on the bed and one of the E-scale's measured weight dropped by 5 lbs., it was not exactly 5 lbs. that was added to the measured weight on the other 3 E-scales. This can be caused by the bed legs not being at the exact spot on the E-scale where it was calibrated (meaning the E-scales are not behaving exactly as they did when they were calibrated) and by the calibration equations having some error.

The E-scales have an analog to digital converter which takes a voltage from the load cells and converts it to a byte measurement. During calibration, the byte readout for 0, 52, and 96 lbs. is recorded in a table. When the E-scale connects to the Raspberry Pi computer, that table is read by the computer. When a measurement comes in from the E-scale when it is in use, the computer uses a linear interpretation equation (Equation 1) to determine the weight of that byte measurement. Any byte measurement above the last calibration point (in our case 96 lbs.) is measured using the gain from the last two calibration points (in our case 52 and 96 lbs.).

$$\boldsymbol{W_i = {B_i}\Big/{(B_2 - B_1)/(W_2 - W_1)}} \qquad \textbf{Equation 1}$$

Where W is weight and B is the Hex value of the reading

However, the E-scales do not exactly behave linearly. In the calibration tests it was noticed that the gain $[(B_2\text{-}B_1)/(W_2\text{-}W_1)]$ for the range from 0-52 lbs. was about 82 bytes/lb. while for the range from 52-96 lbs. the gain was about 79 bytes/lb. This is a small change but does show that

depending on where the weight is distributed, the change from one E-scale may not be the same as the changes from the other E-scales.

Both the change in position on the bed and change in position of the bed on the E-scales caused errors with precision. In extreme cases where the bed leg is completely against a side of the E-scale and a person is sitting on a corner of the bed, as much as 10% weight change has been noticed from when the bed legs were in the middle of the E-scales and the person was on the middle of the bed. While the extreme case is unlikely to happen in real-world testing, smaller changes in the position of the bed legs and the person did occur which likely account for some of the poor precision numbers that were found in the weight loss study.

A few things could improve the precision numbers in the future. The E-scales could be redesigned to have fewer than 4 load cells in each E-Scale. Many digital scales have a single load cell with a mechanical system that balances the weight and allows a bar to press on the single load cell. Another possibility would be to calibrate each individual load cell in the E-scale rather than assuming they all behave identically. This would require more work during the assembly process. A third option would be to design a way to secure the bed legs so that they are forced to remain centralized on the E-scale. Since there are so many varieties of bed frames, this would be very difficult, but some sort of a universal clamping system could be developed. Lastly, the E-scales should be calibrated with more calibration points than the three that were used during the weight loss study and the calibration points should be more condensed in the range where weights are expected to be measured. Since weights below the weight of a bed (100-200 total lbs.) are not important, the calibration points for each E-scale should be focused in the range of about 50 – 150 lbs. on each E-scale (200-600 total lbs. including the bed and person).

All of these issues contributed to the poor performance numbers for the E-scale during the weight loss study, but they are possible to correct as described above. These further developments are needed before the E-scale will be a value to wheelchair users and other markets.

2.5 VERSION 4

2.5.1 Design Description

Based on the focus group and I-Corps market research results in Chapter 1, it was discovered that $200 is the limit that wheelchair users would likely pay for this type of a weight scale. Achieving this price point is difficult with the scales described in Versions 1-3 because they use traditional sensing that can quickly increase costs of the end-product. For instance, the Nexaware version (Version 3) of the system is projected to retail for about $650, and the underlying components costs are approximately $250, which is $50 higher than the target cost for the E-scale. This is one of the reasons Nexaware chose to target the healthcare market, which can bear a higher price per unit cost.

Changes could be made in the hardware design to reduce costs. For instance, the 16 shoulder bolt fasteners ($34 per system) could be replaced with lower cost fasteners and/or fewer fasteners. The Raspberry Pi computer ($35) could also be replaced by a microcontroller at a fraction of the cost.

Each E-scale also has a Bluetooth board that sends the E-scale's weight to the computer. These boards cost about $10 each so wiring some E-scales together or eliminating the need to have 4 Bluetooth boards would reduce costs. One option is to investigate only having 1 or 2 E-scales

recording weight and have the other E-scales be dummy E-scales with the same dimensions to maintain a level bed. This would reduce the cost by tens of dollars for each E-scale that is not measuring; however, these changes are likely to decrease the accuracy and precision, which was described was a design deficiency for versions 1 & 3. Consequently, the approach of using fewer scales may only make sense for the movement applications (i.e. sleep quality, pressure sore risk assessment, and bed exit) where the accuracy and precision of the total weight is not as important as the variance in weight during movements.

Another innovative option that has been investigated to reduce costs would be to turn the case itself into a load cell. A drawing and picture of this prototype are shown in Figure 15 and Figure 16, respectively. Typical load cells use a cantilever beam with a force placed on the free end of the beam and strain gauges to measure the elongation or shortening of the top or bottom face of the beam. In this design, the strain gauges are attached to the plastic ring in a vertical direction to measure the compression of the plastic when the load is placed on top. This could decrease costs by having fewer strain gauges and by requiring less metal components. It also would reduce assembly costs because the strain gauges can be placed on the mold and attached directly to the plastic when it is being molded. A provisional patent application related to this design has been filed.

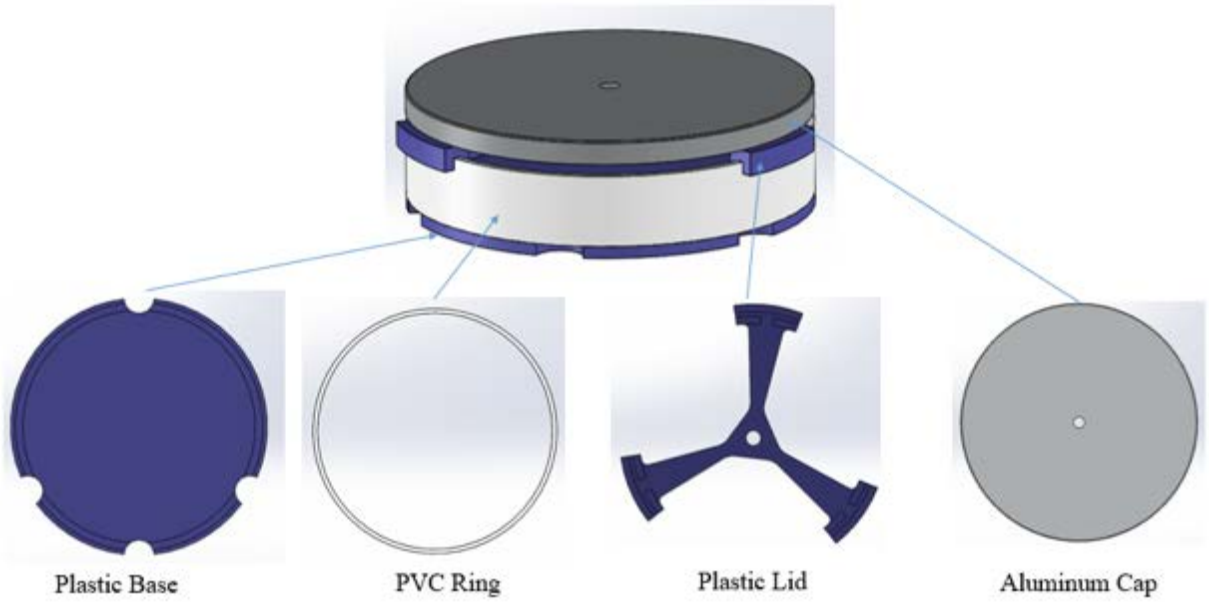


Figure 15: Drawing of Version 4 load cell

Figure 16: Image of Version 4 load cell

2.5.2 In-Lab Testing

Bench testing was completed with a breadboarded single scale that showed promising results. The goal of this evaluation was to characterize the PVC load cell design in order to determine if it is a viable option for future E-Scale products. The resulting data also allow for comparisons between other load cell designs in the future. The following test methods were derived from prior E-Scale test cases but were adapted to fit and better test the characteristics of Version 4.

After the prototyping and fabrication of a single load cell, it was tested in a laboratory environment to characterize its behavior in response to certain test cases. Test methods are delineated in Table 13. An arbor press was used to provide the load in every test case. A digital scale was placed between the load cell and the base of the press in order to measure the force applied by the press. A nut was placed above a marked test point, in order to apply the load from the press exactly at that point. Because it was difficult to achieve an exact force with the press, forces measured by the scale within two pounds of the target were used as acceptable applications of the test force. The output voltages from the strain gauges were recorded as voltage vs. time plots. Each test case was conducted three times.

Table 13: Tests for PVC load cell

Test Name	Test Method
Linearity	Using the arbor press, apply a 50-pound force to the center of the load cell, record the measurement, and then remove the weight. Complete this test for a range of 50 to 300 pounds in 25-pound increments.
Precision	Using the arbor press, apply a force of 300 pounds to the center of the load cell, record the measurement, and then remove the weight. Complete this test five times and compare the standard deviations of the data points.
Off Axis Loading	Prop up the left edge of the load cell with a ¼ inch piece of aluminum, so that the load cell sits on the testing platform at an angle. With the arbor press, apply a 100-pound load, record the measurement, and then remove the weight. Complete this test for a range of 50 to 300 pounds in 25-pound increments.
Off Center Loading	Mark test points on the top face of the load cell every 60 degrees from horizontal at ½-inch and 1-inch distances from the center. Using the arbor press, apply a 100-pound load to a test point and record the measurements. Complete this test for all 12 test points on the load cell's top surface.
Capacity	Load a puck with maximum weight, 300 lbs., and make sure that voltage output is within the readable range, from 0 to 4.5 volts.

2.5.2.1 Results

Linearity Test - Linearity testing of the PVC load cell demonstrated that each strain gauge behaves linearly when loads between 50 and 300 pounds are applied, as seen in the R^2 values reported in Figure 17. The three strain gauges did not react in exactly the same manner, and each set of values had its own gain constant. This test shows the behavior that can be expected from this design throughout the range of test weights.

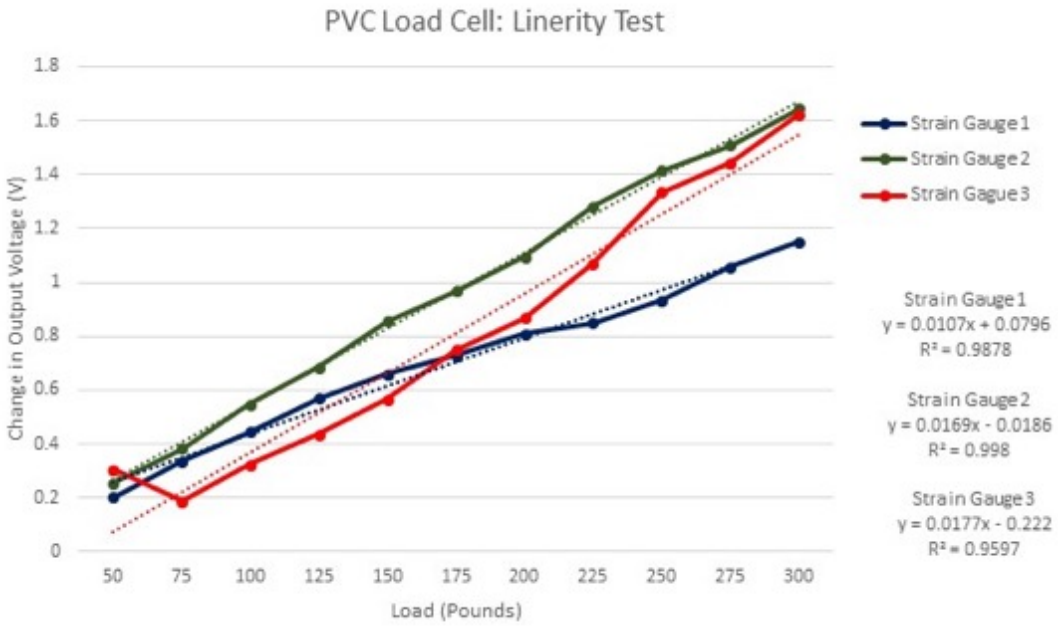


Figure 17: Linearity test

Precision Test - Precision testing shows that each strain gauge has a different level of precision. Using the standard deviations in Figure 18 and the calibration constants in Table 14, it is evident that the deviation between the trials is over one pound, which is the E-scale specification.

Table 14: Precision test

Strain Gauge	Approximate Calibration Constant (V/lb)	Standard Deviation (lbs)
1	0.011	7.394
2	0.017	3.327
3	0.018	11.00

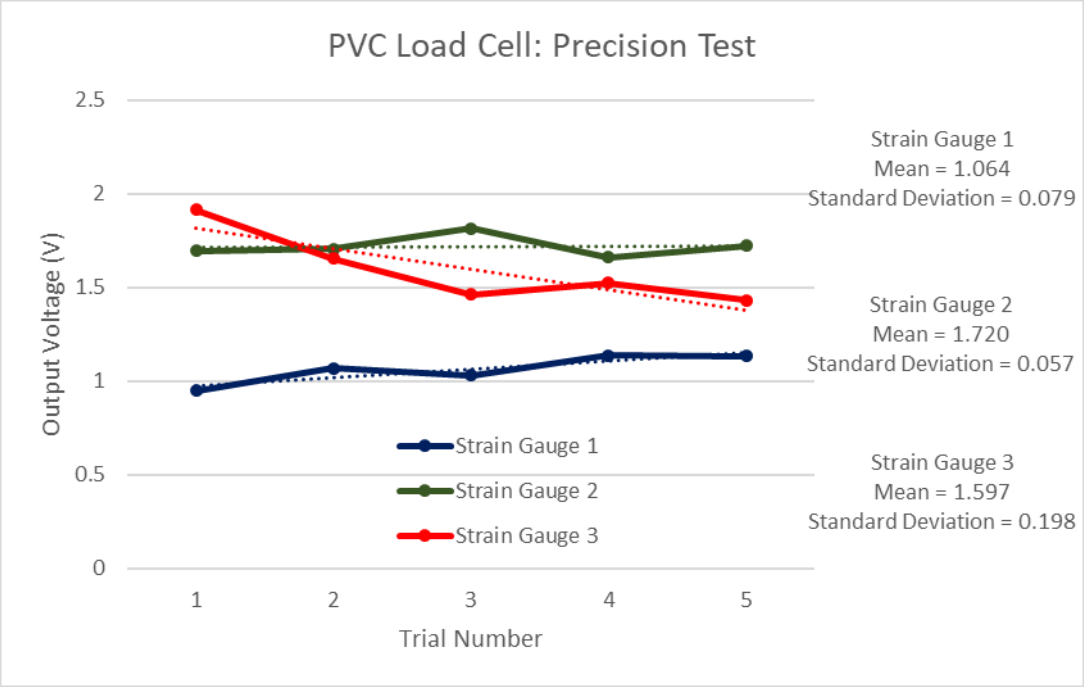
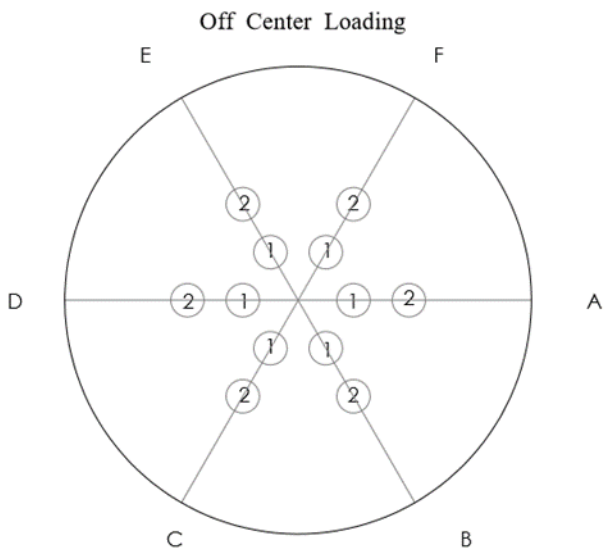


Figure 18: Precision test

Off Center Loading Test - In the off center loading test, with results shown in Figure 19, some outlier data points were excluded from the results in order to better interpret the data. The values from the different test points showed no real pattern in relation to each other. Some test points show high degrees of accuracy, while other are well under the one-pound limit set by the E-Scale specifications.



Position	Percent Accuracy
A1	99.1
A2	99.2
B1	75.2
B2	69.3
C1	72.7
C2	65.6
D1	79.0
D2	78.6
E1	76.5
E2	73.7
F1	84.5
F2	88.2

Figure 19: Off-center loading test

Off Axis Loading Test - In the off axis loading test, with values reported in Figure 20, each strain gauge exhibits linear behavior. However, this behavior is different than that seen in the linearity test. Figure 21 shows how the measured values differed from the target values.

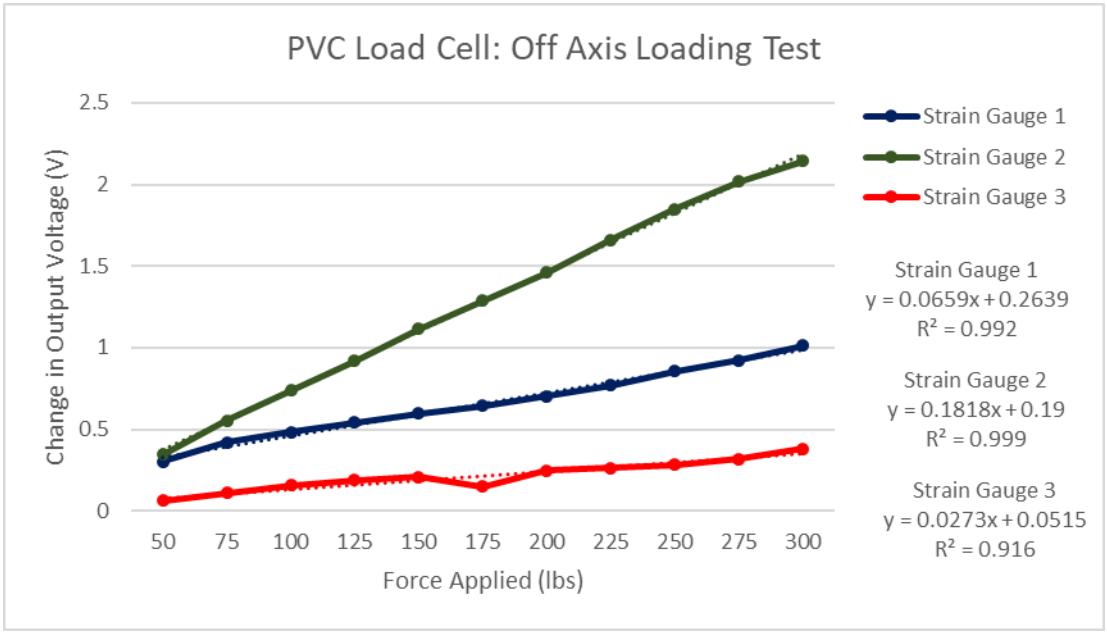


Figure 20: Off-Axis loading test

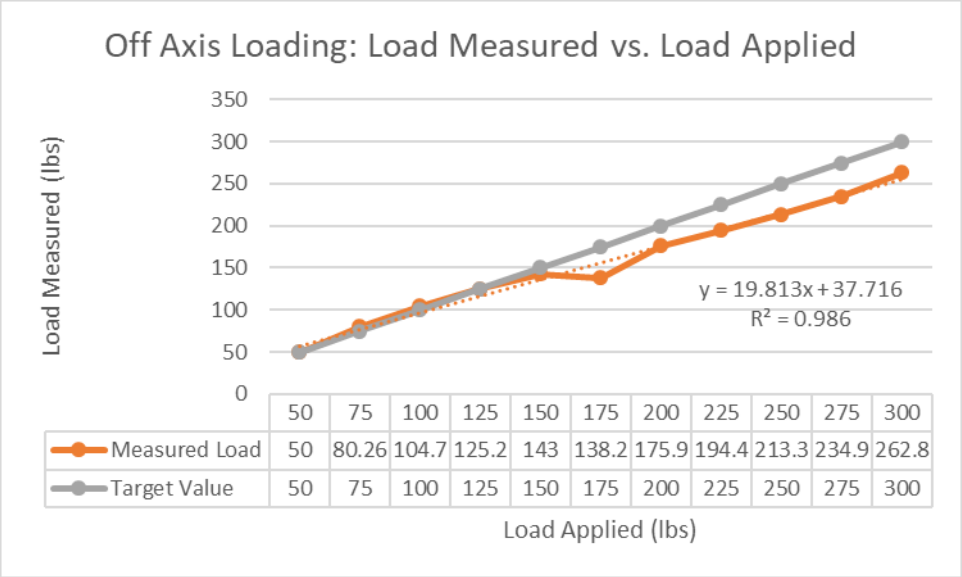


Figure 21: Off-axis measurement vs. applied load

Capacity Test - The capacity test, an aggregation of all other test results, shows that the system responds with a readable output voltage between 0 and 4.5 volts when loaded through the range of 0 to 300 pounds. The highest recorded output voltage range was 2.884 volts, and the lowest was 0.180 volts. A summary of the performance of Version 4 is provided in Table 15.

Table 15: Version 4 performance

Test parameters	Target Value	E-scale performance	Target achieved
Capacity	300 lbs.	300 lbs. (not tested beyond limit)	✓
Accuracy	1.0 lbs.	2.6 lbs.	×
Precision	±1.0 lbs.	± 7.2 lbs.	×
Resolution	0.5 lbs.	0.1 lbs.	✓
Hysteresis	No target	Not tested	NA
Drift	No target	Not tested	NA
Creep	No target	Not tested	NA

2.5.3 Community Testing

This version of the E-scale has not been tested in the community at this point, but the design is also part of the licensed technology to Nexaware who may pursue developing it into a commercial application.

2.5.4 Design Deficiencies

The main deficiency of this version was determined to be the need to better calibrate and optimize the amplifiers for each strain gauge so they behave similarly or to keep calibration values for each strain gauge rather than summing their voltages. Future work should include building a full system and characterizing the system similarly to what was completed with Version 1 of the E-scale in Section 2.2.2.

2.6 OVERVIEW OF E-SCALE ITERATIONS AND LESSONS LEARNED

A table comparing the 4 versions of the E-scale is presented in Table 16.

Table 16: Summary of all E-scale versions

E-scale Version	Version 1	Version 2	Version 3	Version 4
Number of load cells in each sensor	1	3	4	1
Data transfer method	Wired	Wired	Bluetooth	Undetermined
User interface	Bedside display	Bedside display	Android App	Undetermined
Designed and manufactured by	University research lab	University research lab	Nexaware	University research lab
In-Lab Performance				
Capacity	1,200 lbs.	1,200 lbs.	1,200 lbs.	300 lbs. per sensor
Accuracy	1.73 lbs.	1.73 lbs.	< 1.0 lbs.	2.6 lbs.
Precision	0.35 lbs.	0.35 lbs.	Not tested	7.7 lbs.
Resolution	0.5 lbs.	0.5 lbs.	0.1 lbs.	0.1 lbs.
Hysteresis	0.5 %	0.5%	Not tested	Not tested
Drift	0.58 lbs.	0.58 lbs.	< 0.5 lbs.	Not tested
Creep	0.71 lbs.	0.71 lbs.	< 0.5 lbs.	Not tested
Community testing	Ad-hoc in researcher's homes	Chapter 3	Chapter 4	None
Deficiencies	Off center loads	Low weight from carpet	Several listed in Section 2.4.4	Calibration of strain gauges
Approximate Total BOM	$50	$75	$250	Unknown until full system is determined

Design specifications not related to performance (i.e. Accessibility, Automated operation, Installation, Data access, Attractiveness, and Cost) were not tested with all versions, but were considered during design of all versions. They were evaluated during the focus groups and I-corps market analysis interviews in Chapter 1 using Version 1 and assessed at the end of the community testing weight loss study in Chapter 4 using Version 3.

Throughout the process of the design iterations, several issues related to the functionality and performance of the E-scales were identified and corrected. The differences between Version

2 and Version 3 were substantial as the Nexaware company took ownership of the design and manufacturing of the E-scales. A few lessons were learned throughout the process of testing and technology transfer to a company.

Having a formal and standard testing process that is well documented and systematically applied to all versions is important to be able to compare performance of the versions and to clearly identify if specifications were met. The US Food and Drug Administration (FDA) provides regulations for design controls of medical devices which, if followed, would have likely led to better outcomes [48]. In a guidance document, they stress the importance of design controls [49]:

> *"Design controls make systematic assessment of the design an integral part of development. As a result, deficiencies in design input requirements, and discrepancies between the proposed designs and requirements, are made evident and corrected earlier in the development process. Design controls increase the likelihood that the design transferred to production will translate into a device that is appropriate for its intended use."*

While there were standard tests used to evaluate the performance of the E-scales, they were not systematically applied to all of the versions and documented which resulted in some issues not being identified quickly. The testing process should also have been more in depth by testing the E-scales in more situations including on various surfaces (e.g. carpet, wood, tile, etc.) and with various types of bed legs. Also, a systematic test for identifying inconsistencies with weight placement on the bed and leg placement on the E-scales should have been used with all versions. The failure of having and applying these tests resulted in false assumptions about the performance of the E-scales in community testing. One of the patterns that was consistent during this process was the poorer performance of the E-scales in community testing compared to the lab testing. This

was a result of the lab testing not correctly replicating the community use cases and environments. Ulrich and Eppinger describe this as 'robust design' which is how the product performs under non-ideal situations [44]. The in-lab testing procedures generally only tested the E-scale versions under ideal situations and it was not until the community testing with Versions 2 and 3 that the decline in performance under non-ideal situations was discovered. More robust tests should have been conducted and used to inform the go/no-go decisions for sending the E-scales out for the community-testing studies.

The designs would likely have had better performance and design deficiencies would have been detected sooner if we had leveraged standard testing methods. For all future design iterations, a formal set of tests should be developed to characterize the performance of the E-scale in ideal and non-ideal situations. All of the tests described in ASTM International standard E898-88: Standard Test Method of Testing Top-Loading, Direct-Reading Laboratory Scales and Balances [47] should be followed and conducted on various surfaces (i.e. carpet, hard wood, tile, etc.) with various bed legs (wheels, posts, feet, etc.). A specification should be added for off-center loading determine if the new design and system will be acceptable in that non-ideal situation. ASTM International E898-88 describes the test which includes weighing a standard weight at the center and corners of the weighing platform. The error is the difference from the highest to the lowest indication. The specification should be benchmarked against other commercial weight scales but should likely not be more than 2 lbs. A panel of potential end users and stakeholders should also be brought together to review all of the specifications and develop appropriate tests to determine if they are met.

Second, having clear communication with the company that is licensing the technology and making design changes is vital to make sure that the end product meets the expectations for

the system. This relates to the need for clear and complete documentation of design and testing procedures as required by the FDA for medical devices [49]. Since there were so many consultant companies used and turnover of employees inside of Nexaware, much of the design specifications for Version 3 and requirements for the consultant companies were lost. There were several technical issues with Version 3 which were not identified until the product was delivered. Our team should have been more involved in the planning and design phase with the company and helped develop more documentation that may have led to issues being identified before the design was finalized and built. Since the anticipated software functionality was delayed and then never delivered, there were delays in our testing and roll-out of the system as much of the software had to be adapted or redesigned.

It would have likely yielded better results for our studies if Version 2 of the E-scale was modified to correct its deficiencies related to carpet and then it was used for the weight loss study instead of Version 3. It would have given us more control over the quality of the design and manufacturing of the system and there would have been less surprises during testing. Modifications which may have been needed after testing would also have been easier to make because we would have had familiarity with the design and access to all of the software. This would also have allowed Version 3 to go through more rigorous in-lab testing before being used for community testing in future research.

3.0 DETECTION AND CLASSIFICATION ALGORITHMS OF PASSIVE WEIGHT MEASUREMENTS FOR OCCUPANTS WHO SHARE A BED

3.1 INTRODUCTION

Frequent bodyweight feedback is an influential factor in weight loss and maintenance that leads to better health outcomes [32, 33]. For the general population, there is a wide variety of scales that a person can purchase to stand on to monitor their weight in their homes. For people with mobility impairments there are essentially no available scales for them to easily monitor their weight in their homes that do not require standing [50]. Passive activity monitors, like jawbone and Fitbit, are becoming increasingly popular, and smart scales will now connect with these apps and devices to automatically transfer your weight from the scale right to the device. One downfall of these scales is that they are not passive weight monitors, meaning a person has to consciously intend to go stand on the scale for their weight to be measured.

In Chapter 2, we described the development and testing of the E-Scale that was designed for wheelchair users or any other person to be able to passively weigh themselves in their homes [50]. The system consists of weight sensors that are placed under each leg of a bed which sum to be the overall weight of the bed and any/all occupants. While there are beds that incorporate a scale, these beds are expensive, significantly inaccurate and are generally used in clinical settings with only one person using the bed. Unfortunately, summing the weight of all occupants in the bed limits the use of the scale to circumstances where a bed is not shared, which is only the case in approximately 40% of the houses in the United States [51].

The E-scale is designed to be able to be used with any piece of furniture, but it was also intended to typically be used with a bed since it is believed that the bed is the one piece of furniture that would be used on a daily basis and is not regularly moved. The E-scale provides the benefit of being able to weigh the person passively, but the usage conditions of weighing while in bed are fundamentally different than a traditional bathroom scale which could lead to reduced accuracy. For instance, a traditional bathroom scale is used by a single person, but it is typical for a person to share their bed with another person, a pet, or a child which would add extra weight to the measurement. Example data portraying this situation is shown in Figure 22.

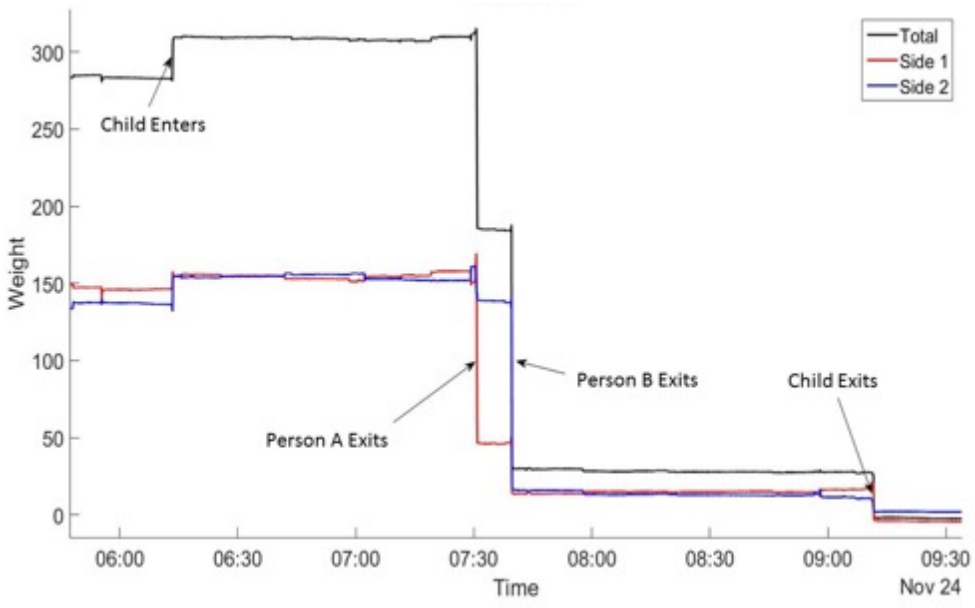


Figure 22: Plot of data collected in the home of a couple with a child. Side 1 and 2 refer to the left and right sides of the bed, respectively.

Researchers have used similar load cell technology under the legs of beds to monitor movements in bed for sleep quality and classifying different types of movements [52, 53], but not for identifying the occupant(s) of the bed. A table about the details of the two studies focused on movement is shown in Table 17.

Adami et al. used a two-algorithm approach where one algorithm detects a movement in bed and the other classifies the movements as large or small [52]. The movement detection algorithm found times where the energy (short-term mean square differences) of the load cell signals was above a threshold. Movement intervals less than 3 seconds apart were combined to be one movement. The window size and thresholds were optimized by testing multiple values and identifying the ones with the best results. The classification algorithm used a wavelet based multiresolution analysis of the data and then a Bayesian combination rule. They achieved a 2.9% equal error rate for the event detection algorithm and 94-96% correct classification rate for the classification algorithm.

Alaziz et al. investigated 3 different feature extraction methods (Log-Peak, Energy-Peak and Zero-X Valley) from the load cell signals and then used a threshold-based approach to detect and classify movements as large or small [53]. For each feature extraction method, they used a subsample of subjects as training data to find an optimal range of thresholds for that method. They then varied the thresholds around those values with all of the subjects to identify the optimal thresholds. They found that using the Log-Peak method, they were able to detect movements at a 6.3% error rate and classify them as large or small movements with a 4.2% error rate.

Table 17: Summary of movement studies

Study	Goal	Technology	Methods	Achieved
Adami et al. (2005)	Detect movement in bed and classify them as large and small	Load cells under each bed leg	**Detection:** Identify windows where mean square differences is above threshold **Classification:** Wavelet based multi-resolution analysis with Bayesian rule	**Detection:** 2.9% equal error rate **Classification:** 94-96% correct
Alaziz et al. (2016)	Detect movement in bed and classify them as large and small	Load cells under each bed leg	Feature extraction of load cell data using Log-Peak, Energy-Peak, and Zero-X Valley. **Detection and Classification:** threshold approach to feature data	**Detection:** 6.3% error rate **Classification:** 4.2% error rate

These studies demonstrated that others have successfully used load cells under the legs of a bed to classify activities that are occurring on the bed. However, these studies have been conducted with a single person on the bed and, to our knowledge, no one has tried to identify multi-person classification. Since 60% of adults in the United states share a bed, knowing who is on the bed is important for any in-home based sensing technology which involves the bed.

The goal for the E-scale is to passively and accurately weigh each person. We determined that the most accurate approach to measure weight is by determining the change in weight from before and after events of interest (i.e. bed exits and entrances) of a single person. This also corresponds to when the bed occupancy changes (e.g. two people to one person). We used a deductive reasoning approach after performing in-lab experiments of two people entering and exiting the bed to come to this conclusion. If the total weight on the bed is measured at different periods of time, information about how the weight changed is lost which can be important to eliminate weight caused by pets, children and bias that may occur due to seasonal changes in bedding.

These events involve large changes in weight rather than small deviations in weight that are used to classify movements in the studies described above. Using the methods of these previous studies as a guide, we used a similar threshold-based approach for our study to detect and classify our events of interest, but by using the continuous total weight of the E-scale and weight from each side of the bed as our data streams for the algorithms. Using this approach to detect events related to the occupancy of the bed, we hypothesized that the overall accuracy of the algorithms would be greater than 85%, which corresponds to roughly 6 of 7 days in a week, and is conservative based on the movement classification studies described previously.

3.2 METHODS

3.2.1 Study Design

Couples were recruited through word of mouth to participate in an IRB-approved study that consisted of installing the E-scale in their homes for 4 weeks. The E-scale was set up with two 'flag' buttons that served as a bed exit and entrance journal and was considered the truth data for when a person entered or exited the bed (Figure 23). Each member of the couple was asked to press their button every time they entered or exited the bed and these data along with the weight of the 4, 5, or 6 individual sensors and a timestamp were saved to an SD card approximately once every second. The E-scale had a button on the display case that would "zero" the current weight. That button also served as a privacy button where the data collection would stop recording for 2 hours or until the button is pressed again. The E-scale was installed by a member of the research team and use of the E-Scale was demonstrated to the couple.

Figure 23: Version 2 of E-scale used for couple study

3.2.2 Algorithm Development

In order to describe the algorithms that were developed and trials that were conducted, the setup of the E-scale and description of the data are needed. For a 4, 5 or 6 post bed as depicted in Figure 24, there are 4, 5 or 6 total sensors with one being placed under each leg of the bed so the entirety of the weight of the bed and any occupants is transferred to the sensors. For the development of the algorithms, we made two assumptions; that a person's weight does not change drastically and abruptly, and that couples sleep on the same side of the bed every night. For these algorithms, we needed to know the side of the bed on which the people sleep and their approximate weight. The data streams used for the algorithms are described in Table 18 below:

Table 18: Data streams for different beds

	Sum of weight from sensors		
Number of bed legs	**4**	**5**	**6**
Total weight	1,2,3,4	1,2,3,4,7	1,2,3,4,5,6
Side 1	1,2	1,2	1,2,5
Side 2	3,4	3,4	3,4,6

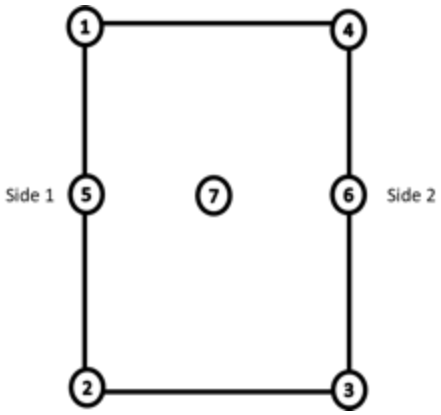


Figure 24: Depiction of E-scale placement for different beds

3.2.3 Event Detection Algorithm

The first algorithm is designed to detect an "event" that is any time one of the two people get into or out of the bed, which correlates to a weight measurement (change in weight). This algorithm is designed to identify events where the total weight on the bed deviates by an amount greater than a specified threshold (T) during a specified window of data (W). This algorithm only uses the total weight data set described in Table 18. The algorithm is applied at each individual total weight data point of the E-scale meaning the windows significantly overlap. For the entire string of data, every window of data is classified as above the threshold or below the threshold based on the following equations.

$$\boldsymbol{if\ Max(W) - Min(W) \geq T \rightarrow above\ threshold} \qquad \textbf{Equation 2}$$

$$\boldsymbol{if\ Max(W) - Min(W) < T \rightarrow below\ threshold} \qquad \textbf{Equation 3}$$

After the data string is classified as above or below the threshold, all successive windows that are classified as above the threshold are combined to be a single event. This is done to identify steady-state periods before and after events. The last step is to identify which of the events that were identified by the algorithm likely correspond to a person getting into or out of bed. These should match the time of the flags from the participants pressing their buttons. This was done by only selecting events in the data where the total weight change from before to after the event was greater than a specified magnitude (e.g. 100 lbs.). This eliminates events caused by children or pets and events caused by movement in the bed rather than a person entering or exiting the bed. The total weight change during the event is determined by the absolute value of the weight change from the steady-state periods directly before and directly after the event.

3.2.3.1 Optimization Process

The event detection algorithm included two parameters that could be adjusted in Equations 2 and 3 to optimize the algorithm; the window size (W) and the Threshold (T). We adjusted W from 2 to 20 seconds and T from 6 to 15 lbs. These ranges were chosen because we felt deviations of less than 6 lbs. would be too rare and more than 15 lbs. would be too large to be considered a stable situation and window sizes of more than 20 seconds would combine separate events into a single event. The events identified were then filtered by selecting only events where the total weight change was greater than 100 lbs. to eliminate events caused by children, pets, or events caused only by movement on the bed.

3.2.4 Event Classification Algorithm

The second algorithm is designed to classify the events based on which of the two people, if either, was responsible for the event. This in essence is assigning a weight measurement to one of the two people or to neither. All three data sets from Table 18 (total weigh and weight from each side of the bed) are used for the development of this algorithm. The absolute value of the difference in weight directly before and directly after each event that was identified with the event detection algorithm are used as the weight change for the three data sets. The weight before and after the event are each calculated as the mean value of the weight collected during the window (W) of the steady-state periods on either side of the event. An example of what the data looks like for an event is shown in Figure 25 and a sample of these values is shown in Table 19. If the total weight change is within a certain range (e.g. +/- 10 lbs.) of the expected weight of one of the two people and the weight change of the sensors on the side of the bed on which they sleep has the greater weight change, then the algorithm assigns that event and weight to that person.

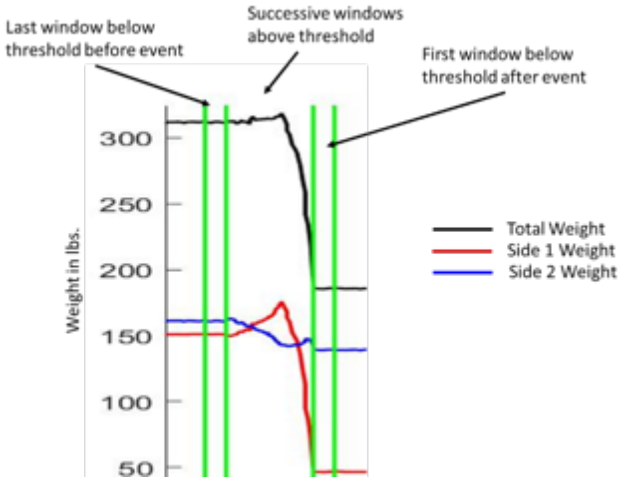


Figure 25: Sample of event data

Table 19: Sample event data

	Total weight	Side 1 weight	Side 2 weight
Window before	311.7	150.8	160.9
Window after	185.9	46.8	139.1
Abs(difference)	**125.8**	**104.0**	**21.8**

In order to maximize the accuracy of the event detection and the event classification algorithms, we varied the window size (W) and the threshold (T) in Equations 2 and 3 individually to determine how they affected the overall accuracy of the algorithms. The accuracy was determined by comparing the classification of the algorithms to the flags entered based on the button presses from the subjects. Because there were several instances of multiple button presses in a short period of time, and other instances where the E-scale data indicated a large weight change but there were no button presses, we developed a set of rules to correct the flags based on review of the data sets. The rules and justifications are described in Table 20.

Table 20: Rules for correcting flags

	Data collected	Interpretation	Action taken
1	Two flags of one user pressed within 10 seconds with one evident event	Only one event happened	Changed to a single flag
2	Flag was pressed with no evident event within 2 minutes	Flag press was incidental	Deleted flag
3	Both flags pressed within 1 minute of an evident event less than 300 lbs.	Ambiguity of which person caused event	Deleted flags
4	A flag was missing for an event directly after or before a flag was pressed for the same weight change happening in the reverse magnitude direction	The person pressed the flag during one event, but failed to press it for the other	Added same flag for the event missing a flag
5	A flag was missing for an event directly before or after the opposite flag was pressed for an event in the same magnitude direction	One person pressed their flag, but the other person failed to press theirs	Added the opposite flag for the event missing a flag
6	An event with a change of more than 300 lbs. occurred with zero or 1 flag being pressed within 2 minutes of the event	One person or neither person pressed their flag, when both caused the event	Made the event identified by both flags

To determine the accuracy of the event classification algorithm, the percentage of the corrected flags that were correctly identified by the algorithms was calculated. For this analysis, 3 criteria had to be met.

1. An event was detected within +/- 1 minute of the flag
2. The absolute value of the weight change during that event was within +/- 10 lbs. of the person that was associated with that flag
3. The side of the bed with the greater absolute value of weight change matched the flag of the person associated with that side of the bed

If these 3 criteria were met, the algorithms for that flag were considered correct. If any of these criteria were not met, the algorithms for that flag were considered incorrect.

3.3 RESULTS

Five couples participated in the study for a total of 140 days of data. A table reporting the number of "flags" that were pressed for the five couples and their weights is provided in Table 21. The number of corrected flags in Table 21 is the result of applying the rules in Table 20.

Table 21: Couple data

Couple	Bed Legs	Days	# of Original flags	# of Corrected flags	Weight 1 (lbs.)	Weight 2 (lbs.)
1	4	29	78	92	161	234
2	4	25	130	106	203	171
3	6	28	88	109	136	185
4	5	30	78	117	128	172
5	6	28	151	116	126	129

3.3.1 Event Detection

The total number of events from the results of these variations of W and T ranged from 1726 – 2287 events. This shows that varying these two parameters had a large effect on the number of events that were detected. The number of events generally increased with T increases and with W decreases.

3.3.2 Event Classification

The results of this algorithm are shown in Table 22. The highest percentages are highlighted. Scatter plots of correctly and not correctly identified flags for Couples 2 and 5 are shown in Figure

26 and Figure 27 respectively. Scatter plots for all five couples are shown in Appendix A. Couple 2 had the best accuracy at 85%. Couple 5 was unique in that the two people's weights were very similar so their weight ranges for classification overlapped. For many of the flags for Couple 5, the classification was solely based on the side of the bed with the larger weight change as the total weight measured would match either person's weight range. The overall accuracy for Couple 5 was 77%.

Table 22: Percent of accuracy compared to flags

		Weight Limit (lbs.)									
		6	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Window Size (seconds)	**2**	71%	69%	69%	68%	67%	66%	65%	65%	65%	65%
	4	74%	73%	73%	73%	74%	74%	73%	73%	72%	71%
	6	75%	76%	76%	76%	77%	77%	77%	76%	76%	76%
	8	75%	75%	75%	75%	76%	76%	76%	76%	76%	76%
	10	74%	75%	74%	75%	75%	76%	76%	76%	76%	76%
	12	73%	74%	74%	74%	75%	75%	75%	76%	75%	75%
	14	71%	73%	73%	73%	73%	74%	74%	74%	74%	74%
	16	70%	72%	72%	72%	72%	73%	73%	73%	74%	74%
	18	70%	70%	71%	71%	71%	72%	72%	72%	73%	74%
	20	68%	69%	70%	70%	71%	71%	71%	72%	72%	72%

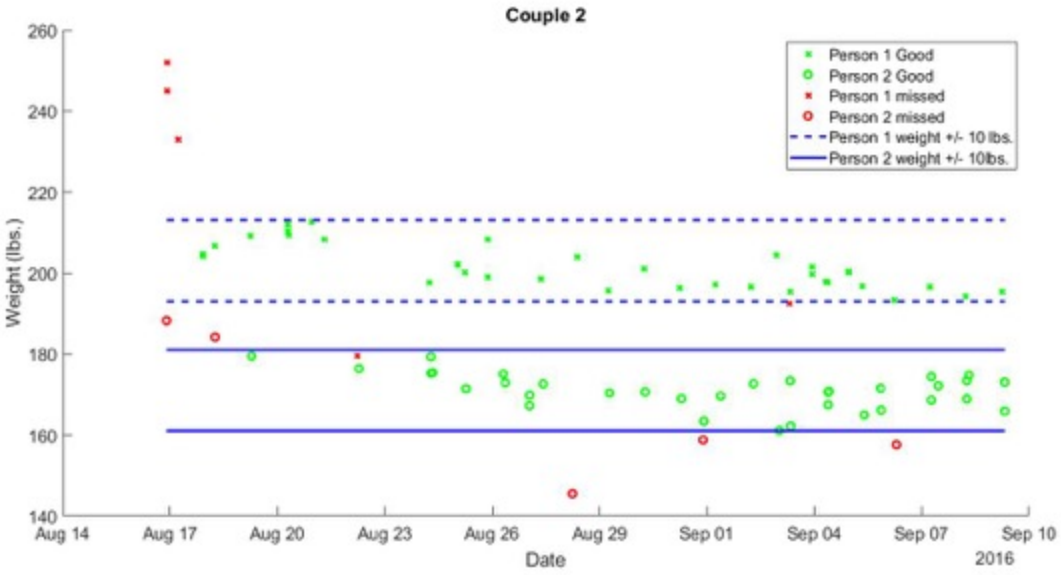


Figure 26: Couple 2 classification

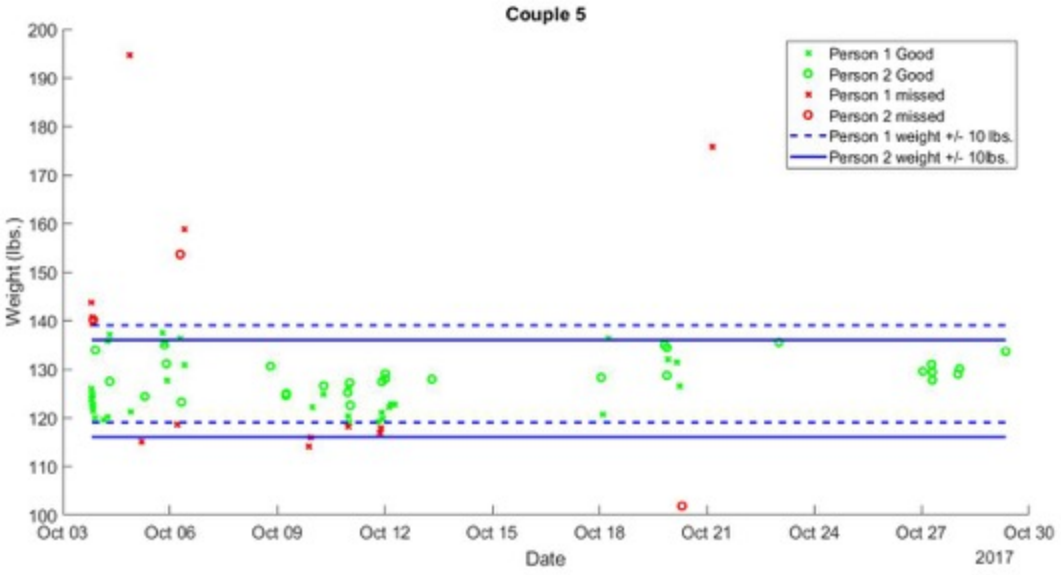


Figure 27: Couple 5 classification

3.4 DISCUSSION

This study shows how the E-scale can be used to detect when a person enters or exits a bed and identify who that person is so that it can assign a weight measurement to the correct person. Five subjects participated in this study by using the E-scale for 4 weeks and recording when they entered or exited the bed. The algorithms developed achieved a 77% accuracy level for identifying when someone entered or exited the bed and classifying that person correctly.

3.4.1 Event Detection

The accuracy of the event detection algorithm was sensitive to the parameters selections (W & T). The results were intuitive in that having a smaller window results in more events detected because as the window gets larger, close events were merged into one event. Both too small of a window and too large of a window can be problematic for the accuracy of the algorithm. If the window is too small, one event may be classified as two events such as if a person sits still on the side of the bed for a few moments before fully getting into the bed. This would split their total weight between two events and not be accurate. Alternatively, if the window is too large, two events could be classified as one, such as when both people get into bed at approximately the same time with no steady-state period between the events. This occurred several times in our data. This is likely the cause of the general decrease in accuracy as W is increased higher than 6 seconds as shown in Table 22.

It is also intuitive that as the threshold gets larger, it can detect more events. This comes from more events being detected that are happening close to one another. With a low threshold one person may get into bed and continue to fidget or move around for a few moments until the

other person gets in. With a low threshold, these events would be combined into one event, while a higher threshold requires less stabilization to end an event. However, a high threshold could mean that the weight recorded for that event is less accurate if the weights before and after the event are not as stable. Taking both the window and threshold into account, it is logical that the smaller window and larger threshold have the most predicted events.

By looking at graphs of the data and comparing those to the flags that were pressed by the subjects, it was evident very early in the process that the participants did not press their buttons very consistently; especially when getting out of bed in the morning and short exits in the middle of the night, presumably to use the restroom or to check on children. This however, did confirm the need for a passive algorithm to determine the weight of someone using the E-scale because even remembering to press a button when entering or exiting the bed proved difficult. The button also had a light that lit up when the person pressed it which stayed on until it was pressed again. Couple 2 in particular had an issue with how bright the lights were when they were trying to sleep, so they usually pressed the flag buttons twice to turn the light back off. This explains why they, in particular, had so many more original flags in Table 21 than the other couples and why Rule 1 was included to correct the flags as much as possible without compromising the data.

3.4.2 Event Classification

Typical classification algorithm developments include using some kind of logic or decision tree, a regression equation, machine learning or k-nearest neighbor approaches. For this situation, using a logic threshold-based approach was determined to be most appropriate. K-nearest neighbor, regression and machine learning all need training sets to develop the algorithms. Since the users' weights (and difference between their weights) would be different for every couple who uses the

E-scale, the training data from our study would not likely be applicable for each individual couple. Also, by default, these approaches force data into a classification, so they would need to have some logic associated with them to filter out any outlying data. To use these classification approaches, they would have to be designed in a way for the algorithms to adapt to the people's weights trying to use it.

The analysis to determine the accuracy of the algorithms that were developed compared to the flags was done to determine the sensitivity of the algorithms, or the ratio of true positives to false negatives. Meaning of events that were believed to be true (flags), how many of those events were found by the algorithms versus how many were not found. This inherently ignores any false positives that the algorithm detected, but since so many flags were skipped by the subjects, this is not necessarily important at this stage. Also, it is very unlikely that the algorithms would detect a weight change of over 100 lbs. when neither person entered or exited the bed. The only conceivable instances for this would be the presence of a very heavy pet or another adult using the bed.

3.4.3 Limitations

The 77% accuracy for the algorithms was lower than hypothesized (85%). By analyzing whether the weight change variable or side of the bed variable contributed more to the low accuracy numbers, it was by far the weight changes that limited the accuracy. Looking at only events that were within +/- 10 lbs. of either of the couple's weights, the accuracy percentage was 92%. This could be because of a lower than optimal accuracy of the load cells and E-scale in general or because the weight changes detected were for more than a single person. If both participants got into or out of bed at approximately the same time, then it was classified as a single event with a weight change much larger than either person's expected weight +/- 10 lbs. Also, most of the

participants had pets and/or small children which regularly slept with them so if they entered or exited the bed at the same time as a participant then their weight would be included in the weight change measurement.

Five couples is a small sample size for developing algorithms which will be used outside of a controlled lab environment. However, the simplicity of the algorithms will likely lead to them being robust in in-home environments. By observing graphs of the data, it was evident that many events were not flagged by the participants. As mentioned previously, couple 2 in particular also had many flags which were just meant to turn the light of and didn't correspond to an event. It likely would have resulted in a more complete and accurate data set if the events were flagged by a proximity sensor on a wrist band or some other way of identifying when one of the two subjects got into or out of bed rather than asking them to press a button.

3.4.4 Commercial Potential

In a commercial version, it is envisioned that any weight measurements that are not within an expected range of one of the two people would be discarded or held until the users could in some way confirm or deny the weight. This would mean the loss of some data points, but what is left would be a better representation of the person's actual weight data.

For a commercial version of the E-scale to be effective, a few additional features should be included. First, since the algorithms need to know the weight of the two people and the side of the bed on which they sleep, these items would need to be determined. This information could be gathered as part of the installation of the E-scale by having a process such as asking each person to lay on the side of the bed that they sleep on and measuring their weight at that time. The E-scale could also be programmed to determine these parameters after a period of time using cluster

analyses or other advanced algorithms that would identify common occurrences in the data. It would also be best if the expected weight of each person is routinely updated based on recent measurements so if someone is gaining or losing weight, the algorithms remain accurate.

3.5 CONCLUSION

Since more than 60% of American adults share their bed with a significant other, any monitoring device using the bed should be able to distinguish between the people occupying it. The E-scale is a bed weight monitoring device and this study demonstrated an approach for how to distinguish between the weights being measured for two people sharing a bed. The event detection and event classification algorithms showed promise for this application, but improvements should be made to the E-scale to provide better accuracy for these algorithms to be fully effective in a commercial version of the E-scale.

4.0 DAILY WEIGHT FEEDBACK FOR PEOPLE WITH MOBILITY IMPAIRMENTS

4.1 INTRODUCTION

Despite the higher prevalence of obesity and weight-related comorbidities among wheelchair users and those with disabilities, few weight loss interventions have targeted this population [4, 6, 54-59]. Some sources show the prevalence of obesity among people with disabilities to be as much as 2.5 times that of the general population [4-6] with those with more severe disability having greater obesity risk factors even when only those with the ability to stand independently were included [6]. This means that the numbers may be even higher for wheelchair users. In fact, one study looking at 125 wheelchair users found 70% of them to be overweight or obese [40]. People with disabilities also have a higher rate of obesity-related chronic conditions with 4 times as many having diabetes [6]. People with physical disabilities also have more of a challenge maintaining a healthy lifestyle due to barriers to exercise and daily activities, accessibility barriers [9], attitudinal barriers towards disability and health [10], psychological decline [8], barriers for maintaining dietary needs over time, and dependence of activity on the type of disability [11]. Since obesity and diabetes themselves can lead to a person having impaired mobility, the combination of physical impairment and obesity can be a vicious cycle with one compounding the other [60]. An article in the American Journal of Preventative Medicine in 2011 titled “Obesity and Disability: Time to Act”, summarizes the complications of the combination of obesity and disability and discusses why this is an important topic that needs to be addressed by researchers [4]. They conclude that: “Reducing obesity among people with disabilities who represent 20% of the

population and who experience greater health risks may lower the national prevalence of obesity and lead to improved health and functioning for the group" [4].

It is clear that developing weight loss interventions for people with mobility impairments, specifically wheelchair users, needs to be further investigated. In a review of behavioral techniques used in weight loss interventions for people with impaired mobility, Plow et al. called for research to draw on successful approaches for the general population while adapting interventions for specific issues related to the population of people with impaired mobility; specifically, transportation and emotional-regulation issues [60].

One of the primary tenants of behavioral lifestyle interventions for weight loss is self-monitoring of diet, exercise and weight [61, 62]. As mentioned in Chapter 1, wheelchair users do not have access to affordable and accessible weight monitoring technology in their homes. Literature reviews and meta-analysis studies have shown that regular weight feedback along with a weight loss intervention leads to better weight loss or better weight maintenance than the intervention alone [31-33]. Of the 17 studies included in one review, all 17 showed that interventions with regular self-weighing were more effective than interventions without regular self-weighing [33]. However, this research has always been performed with individuals who can ambulate independently because there is little technology available for wheelchair users to measure their weight frequently and independently in their homes. It is hypothesized that not having access to regular body weight feedback contributes to the increased prevalence of obesity among wheelchair users. If the general population could not regularly weigh themselves to see if weight loss efforts were having an effect, evidence suggests that fewer people would be successful in changing lifestyle behaviors and there would be even higher numbers of people who are

overweight or obese. This is currently the case for wheelchair users as they typically only get weighed during physician appointments and even then, it is not a standard practice.

Maybe the most well-known and universally used behavioral weight loss intervention in research is the Diabetes Prevention Program (DPP) lifestyle intervention, which was shown to decrease the risk of type 2 diabetes by 58% [63-66]. Researchers at the University of Pittsburgh adapted the DPP to be delivered in a group setting called the DPP Group Lifestyle Balance (DPP GLB) [67, 68]. It has also been shown to be effective in lowering weight and increasing physical activity among participants [69-72]. A further adaptation of the DPP GLB has been created and preliminarily tested for people with mobility impairments called the GLB AIM (Adapted for people with Impaired Mobility) [41, 73, 74]. The GLB AIM studies found weight loss was achieved among their study participants and interestingly, not having access to self-weighing equipment was listed as a limitation of the GLB AIM preliminary studies [41].

The goal for this study was to test the accuracy, precision, and feasibility of the E-scale in a real-world scenario where wheelchair users were enrolled in a GLB AIM weight loss study and used the E-scale to weigh themselves daily.

4.2 METHODS

4.2.1 Subjects

Nine overweight or obese (BMI $\geq$ 27 and $\leq$ 40) adult (age 18-80) wheelchair users who were interested in losing weight were enrolled in this study. Table 23 shows the inclusion and exclusion criteria for enrollment into the study.

Table 23: Inclusion and exclusion criteria

Inclusion Criteria
• Use Wheelchair as primary means of mobility • Use a bed with 4 legs • BMI ≥ 27 and ≤ 40.0 • Age 18-80 • Has daily access to Internet to access LoseIt website and/or app and weekly chat meeting (Adobe Connect) • Currently owns or willing to use an android device • Ability to provide informed consent • Ability to provide physician's clearance to participate in a weight loss intervention
Exclusion Criteria
• Presence of an unstable condition requiring physician-supervised diet and exercise (e.g., diabetes, recent myocardial infarction) • Presence of a condition precluding engagement in exercise at moderate intensity (e.g. asthma, congestive heart failure, etc.) • Pregnancy or intention to become pregnant during study • Currently being treated for any psychological issues or problems, taking any psychotropic medications, or receiving treatment with psychotropic medications within the previous 6 months • Reported alcohol intake > 4 drinks/day • Reported participation in a formal weight loss program, loss of ≥ 5% weight in the past 6 months, or current use of weight loss medication. • History of bariatric surgery (lap-band, gastric bypass, etc.) • Planned extended vacations, absences, or relocation during study • A score ≥ 20 on the Center for Epidemiologic Studies Depression Scale (CES-D) [75] • A classification of anorexia nervosa, bulimia nervosa or binge eating disorder on the Eating Disorder Diagnosis Scale (EDDS) [76]

4.2.1.1 Inclusion Justification

1. Use a wheelchair as their primary means of mobility
    a. Rationale: This study was designed for wheelchair users to be the population of interest. Some people only use wheelchairs for long trips or for a few days a week, but we only wanted to include people who use wheelchairs every day and as their primary mode of mobility.
2. Uses a bed with 4 legs
    a. Rationale: Version 3 of the E-scale that was used for this study only had the capabilities for a 4-scale system.
3. BMI ≥ 27 and ≤ 40.0
    a. Rationale: Only people who are overweight or obese should be included in a weight loss protocol. People who are normal weight or underweight would not be recommended to lose 7% of their body weight. People who are morbidly obese would be recommended to lose weight but would need more specific attention than this particular protocol. Morbid obesity is also associated with increased risk of cardiovascular, metabolic, and/or respiratory complications which are exclusion criteria.
4. Age 18-80
    a. Rationale: Only healthy adults were included in this study
5. Has daily access to Internet to access LoseIt website and/or app and weekly chat meeting (Adobe Connect)

    a. Rationale: The LoseIt! website and/or app and weekly chat meeting on Adobe Connect were key parts of this study protocol. As such, the participants needed to be able to access them using the internet.
6. Currently owns or willing to use an android device
    a. Rationale: The app for Version 3 of the E-scale was only developed for the Android platform.
7. Ability to provide informed consent
    a. Rationale: Participants needed to show that they understood the study protocol and were willing to participate and comply.
8. Ability to provide physician's clearance to participate in a weight loss intervention
    a. Rationale: To make sure that the participants would not be at risk for complications for any conditions for which we did not screen, we wanted a medical doctor to also provide clearance for the subject to participate.

4.2.1.2 Exclusion Justification

1. Presence of an unstable condition requiring physician-supervised diet and exercise (e.g., diabetes, recent myocardial infarction)
    a. Rationale: Individuals with these types of medical conditions could require additional clearance, supervision, and changes in the prescription of dietary and physical activity goals, which was outside of the projected scope of this study. These types of alterations would be different from the standard procedures used within the intervention of this study.
2. Presence of a condition precluding engagement in exercise at moderate intensity (e.g. asthma, congestive heart failure, etc.)

    a. Rationale: The ability to perform physical activity was a necessary component in this protocol. This type of limitation would have reduced the capability of making changes to physical activity behaviors as a part of the weight loss study.

3. Pregnancy or intention to become pregnant during study
    a. Rationale: Pregnancy would have required modification to the intervention and may have required additional medical monitoring. Weight gain during pregnancy would have confounded the outcomes of this study.
4. Currently being treated for any psychological issues or problems, taking any psychotropic medications, or receiving treatment with psychotropic medications within the previous 6 months
    a. Rationale: Interventions for psychological issues may have affected compliance, potentially confound the effect of the proposed intervention, or may require additional medical monitoring throughout the study period. Psychotropic medications are exclusionary as certain types have been shown to affect body weight.
5. Reported alcohol intake > 4 drinks/day
    a. Rationale: Alcohol contains empty calories and causes metabolism of other foods to slow down which can make weight loss difficult and would confound the effects of the proposed intervention.
6. Reported participation in a formal weight loss program, loss of ≥ 5% weight in the past 6 months, or current use of weight loss medication
    a. Rationale: Use of other efforts to lose weight (other formal weight loss program or weight loss medication) would confound the effect of the proposed

intervention. If the person lost more than 5% of their body weight in the last 6 months, they should focus on the prevention of weight regain rather than weight loss.

7. History of bariatric surgery (lap-band, gastric bypass, etc.)
    a. Rationale: Bariatric surgery may have required alterations in the proposed diet and physical activity intervention and may have confounded the outcome variables for this study.
8. Planned extended vacations, absences, or relocation during study
    a. Rationale: Individuals planning extended absences from home or relocating may have not completed the study, which would have increased attrition. They also would not be able to use the E-scale if they were not at home.
9. A score ≥ 20 on the Center for Epidemiologic Studies Depression Scale (CES-D)
    a. Rationale: Psychological issues may have affected compliance and potentially confounded the effect of the proposed intervention.
10. A classification of anorexia nervosa, bulimia nervosa or binge eating disorder on the Eating Disorder Diagnosis Scale (EDDS)
    a. Rationale: The presence of an eating disorder may have confounded the results of this study by making lifestyle changes to eating habits more difficult.

4.2.2 Recruitment and Screening Procedures

Subjects were recruited from the Human Engineering Research Laboratories wheelchair registry and CTSI Pitt+me research registry at the University of Pittsburgh. They also were recruited through flyers distributed to wheelchair clinics and disability groups in the Pittsburgh area. Potential subjects were screened on the phone based on the Screening Questionnaire in Appendix B to determine eligibility of most inclusion and exclusion criteria. If they met all of the criteria, the subjects were invited to come to the Human Engineering Research Laboratories where they were consented and evaluated for other more personal and official eligibility measures. Specifically, they were given the Center for Epidemiologic Studies Depression Scale (CES-D) [75] and the Eating Disorder Diagnosis Scale (EDDS) [76] questionnaires (Appendix C and Appendix D respectively) to determine if they might be depressed or have an eating disorder. If they scored a 20 or higher on the CES-D or were classified as having anorexia nervosa, bulimia nervosa or binge eating disorder on EDDS, they were excluded from the study and referred to health professionals in those fields at UPMC and/or the VA. Individuals who were still eligible then had their height and weight measured in the lab to determine their BMI. If the BMI measure fell inside of the inclusion range (≥ 27 and ≤ 40), they were eligible to participate and enrolled in the study.

4.2.3 Study Design

This study was a 13-week feasibility study where the wheelchair users were recruited in a single cohort and all received a standard behavioral weight loss intervention [77] which was adapted specifically for wheelchair users and people with impaired mobility from the DPP GLB program

(GLB AIM) [41]. LoseIt! [78] was installed on the participants' phones at their baseline measurement visit. The participants were asked to record their food intake and exercise every day using the LoseIt! mobile app or website. They also had the E-scale installed in their homes and were asked to weigh themselves daily using the E-scale and to log that weight into LoseIt!. Weekly group chat meetings were conducted by a Registered Dietitian nutritionist trained in behavioral weight loss strategies [79]. Discussions centered around the weekly topics previously emailed to the participants. The participants were able to share their successes and challenges with the group so that they could learn from and support one another.

4.2.4 Standard Behavioral Treatment Intervention

The overall goal for the participants in the study was to lose 7% of their bodyweight through a combination of decreasing caloric and fat intake and increasing physical activity. The GLB AIM program was previously used in a study that found 7.4% weight loss of the study completers (N=7/10) and a 4.6% weight loss using intention-to-treat analyses (N=10) [41].

4.2.4.1 Calorie Goals

The calorie goal for each participant was calculated from the individual's baseline body weight as shown in Table 24. These calorie and fat goals were based on intake recommendations that have been successful in other weight loss programs and are consistent with the USDA Dietary Guidelines [80]. To promote adoption and adherence to these recommendations, participants were provided with training in the first two weeks of the program on how to read nutrition labels and how to monitor the food they were eating using the LoseIt! app.

Table 24: Calorie and fat intake recommendations

Weight (lbs.)	Fat Goal (grams)	Calorie Goal
120-174	33	1,200
175-219	42	1,500
220-249	50	1,800
>250	55	2,000

4.2.4.2 Behavior Physical Activity Goals

The physical activity goals were standard goals used in other DPP GLB studies (gradually increase overtime towards a goal of 150–200 minutes of moderate-intensity exercise per week) [68]. The educational material that was used from the GLB AIM curriculum has been adapted specifically for wheelchair users by an advisory panel and by comments from the initial study participants [74]. Information about accessible gyms and adaptive sports clinics in the Pittsburgh area was also provided.

4.2.4.3 Behavioral Treatment Group Sessions

The cohort received an online standard behavioral weight loss program that focused on diet, physical activity, and behavioral strategies to support making lifestyle changes conducive to weight loss. This intervention used the curriculum from the GLB AIM program. The cohort met every week (except the final week) until the 13-week intervention was completed for a total of 12 online group sessions. Subjects received nutritional and behavioral counseling; practical experiences to develop skills to implement a healthy lifestyle (e.g., practice mindful eating, portion size, modify foods or meals to reduce fat content) and homework assignments (reorganizing kitchen/pantry to make healthy food options more visible) during the 12, 60-min group sessions

(see Appendix E for the 12 session topics) [41]. These sessions were led by an interventionist experienced in providing standard behavioral weight loss treatment online [79]. The protocol for the sessions was to provide the weekly lesson to the participants a few days prior to the online meeting so they could review the material before the meeting. They were also provided a link to the Adobe Connect meeting which had the audio and video disabled. During the meeting, the interventionist covered the material in the lesson while encouraging participants to share their experiences with the group. Subjects who missed a scheduled meeting were contacted by the interventionist the next day by email and the transcript from the chat session that they missed was attached to the email.

4.2.5 Monitoring

All participants were given login credentials to a LoseIt! premium account, an online self-monitoring journal that can be accessed via their smartphone and computer [78]. This software permits self-monitoring of diet, exercise, and weight. It also provides a database of more than 7 million foods. The database shows participants the nutrient value of each food and calculates the subtotals. Date and time of each entry is recorded. The Ascendapp for LoseIt!, a portal created by LoseIt! for centralized user management, was utilized by the interventionist for monitoring participant journal entries. Participants were provided weekly feedback on their LoseIt! journal entries by the study interventionist and were able to read their individualized feedback in the LoseIt! app or website. The Ascendapp also allowed the study team to view participants' entries and set custom controls and reminders on their use. The study team monitored the compliance of the cohort by recording how often they updated their weight in LoseIt!. All participants were encouraged to monitor their weight by reading their weight from the E-scale android app and then

recording it into the LoseIt! app. This was done to guarantee that the participant actually looked at their weight measurement. The study team had access to the participants' LoseIt! journals so they could contact a participant if there was any concern about the reported eating and exercise behaviors.

4.2.6 Measurements

At the end of the study, a questionnaire was given to the subjects to evaluate the participant's satisfaction with and helpfulness of individual program items including the E-scale (Appendix F). Summary statistics were used to describe the participants' opinions about the program and E-scale. They were also given the System Usability Scale (SUS) (Appendix G) to evaluate how usable the participants thought the E-scale was for them [81].

The accuracy of the E-scale was determined by comparing the first 3 and last 3 weights recorded in LoseIt! to the baseline and final weight respectively, taken from a calibrated roll-on scale during the in-person meetings at the beginning and end of the study. The average difference and standard deviation were calculated, as well as the percent of measurements that were within 2 lbs. The precision of the E-scale was determined by identifying how many successive measurements (day-to-day) were within 2 lbs. from one another. After the e-scale was returned at the end of the study, we also calculated accuracy and precision of the E-scale data by applying the event classification algorithm from Chapter 3 to the stream of data recorded on the E-scale's computer. Accuracy was again calculated by determining the average difference of the first 3 and last 3 weights from the E-scale to the baseline and final weight respectively, taken from a calibrated roll-on scale during the in-person meetings at the beginning and end of the study. Precision was calculated by determining the average difference between each weight and the linear trend line of

the weights. These data also allowed for presenting data on the number of times that a participant got into and out of bed and the percentage of the day that they were in bed.

To evaluate the effect of the program as a whole, baseline and final measurements were taken at the beginning and end of the 13-week session. These measurements included weight, abdominal girth, and body fat percentage. Paired, one-tailed t-tests were performed on the weight, abdominal girth, and body fat percentage variables to see if they significantly improved from baseline to the end of the study. Also at the end of the study, descriptive statistics were calculated for retention in the study and compliance with attendance at the weekly meetings and recording diet, exercise, and weight in LoseIt!. A study flowchart is provided in Figure 28.

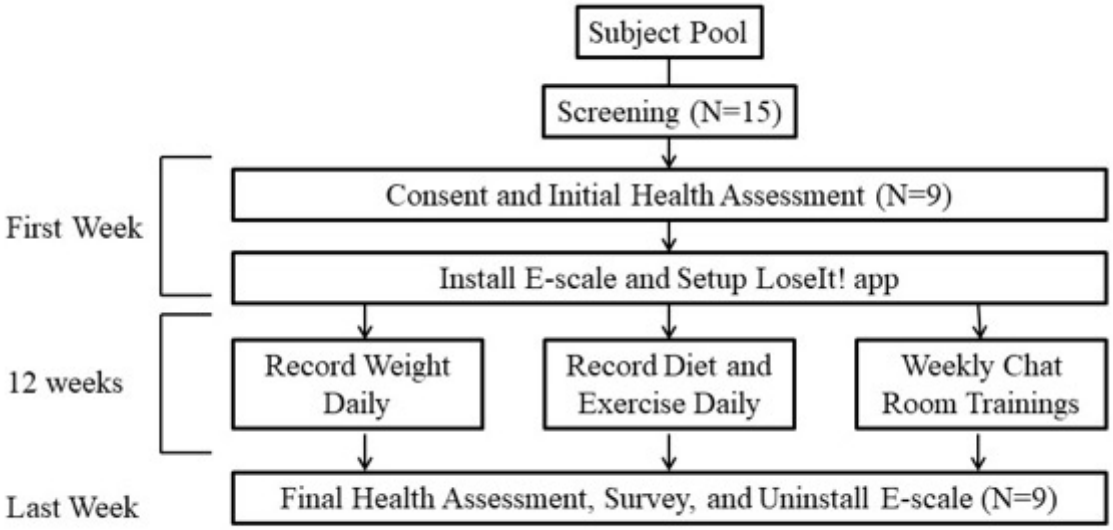


Figure 28: Study design flowchart

4.3 RESULTS

The primary demographics for the 9 participants in the study are shown in Table 25. A full table of all demographic questions is presented in Appendix H. The description of the nine participants weight, abdominal girth, and body fat percentage changes are shown in Table 26. The significance was determined using one-tailed, paired t-tests. A full table of these measurements is presented in Appendix I.

Table 25: Demographics for weight loss study

Demographic	Average (Standard Deviation)
Gender	5 Male; 4 Female
Age (yrs.)	48.8 (15.6)
Initial Weight (lbs.)	196.0 (38.0)
Initial BMI	33.6 (3.7)
Initial Abdominal Girth (in.)	45.1 (5.6)
Initial Body Fat Percent	33.3 (10.5)
Initial Center for Epidemiology Studies-Depression (CES-D) score	4.8 (3.6)
Self-Rated Abilities for Health Practices Scale	90.6 (8.3)

Table 26: Results of weight loss study

Measurement	Baseline Average	Final Average	Change (P-value)
Weight	196.0 lbs.	192.8	-3.2 lbs. (0.098)
Abdominal Girth	45.1 in.	44.4	-0.7 in. (0.127)
Body Fat Percentage	33.3 %	32.9%	-0.4% (0.284)

4.3.1 Retention and Compliance

All 9 participants completed the study and were available for final measurements. The participants attended 74% of the weekly chat room meetings. Seven of the 9 participants used LoseIt! at least 5 out of 7 days for every week of the study. One participant never used LoseIt! and another did not self-monitor 3 of the 12 weeks. The participants recorded their weight in LoseIt! 23% of the possible days. A full table of the weights recorded in LoseIt! is presented in Appendix J.

4.3.2 E-scale Accuracy

The accuracy of the E-scale was determined by averaging the first 3 and last 3 weights recorded in LoseIt! and comparing those values to the baseline and final weights measured using the roll-on scale at the lab. Overall, the E-scale was different from the weights measured by the roll-on scale by an average of 13.5 lbs. with a standard deviation of 5.9 lbs. Only 9% of the first 3 or last 3 weight measurements were less than 2 lbs. away from their baseline or final weights. Table 27 shows the accuracy results for the 8 participants who recorded weight in LoseIt!. After discovering a technical issue (discussed in Section 2.4.4) which caused the E-scale to read low, especially when it was on carpet, changes to the E-scales for subjects 1, 2, 5 and 7 were made which improved accuracy for all of those subjects.

Table 27: Accuracy results

Subject	Baseline Difference (lbs.)	Final Difference (lbs.)
1	20.3	5.3
2	22.2	11.2
3	10.3	36.3
4	10.3	33.0
5	7.7	2.0
6	5.6	2.8
7	12.7	11.1
8	-	-
9	10.1	14.6
Average	**12.41**	**14.53**

4.3.3 E-scale Precision

The precision of the E-scale was determined by calculating the difference of consecutive measurements from the E-scale. On average, the measurements varied by 5.4 lbs. between measurements for all participants. Forty percent of the consecutive measurements were within 2 lbs. of one another.

4.3.4 E-scale Usability

The results from the final questionnaire (Appendix F) and the System Usability Scale (SUS) (Appendix G) are shown in Table 28. These survey items where all 7-point Likert scale questions and the SUS score can range from 0-100. Full tables of the results of these two questionnaires are presented in Appendix K.

Table 28: Results of questionnaires

Survey Item (1-7) **1=Completely Negative; 7=Completely Positive**	**Average Score (Range)**
1. Rating of Education Materials Satisfaction	5.2 (1-7)
1a. Rating of Education Materials Helpfulness	5.8 (5-7)
2. Rating of Online Meetings Satisfaction	5.7 (1-7)
2a. Rating of Online Meetings Helpfulness	6.3 (5-7)
3. Rating of LoseIt! Journal Satisfaction	5.3 (1-7)
3a. Rating of LoseIt! Journal Helpfulness	6.0 (2-7)
4. Rating of E-scale Satisfaction	3.2 (1-7)
4a. Rating of E-scale Helpfulness	3.1 (1-6)
5. Satisfaction with the overall program	5.3 (1-7)
6. Likelihood of recommending the program to other wheelchair users	6.2 (5-7)
7. The E-scale was easy to use	5.8 (1-7)
8. The E-scale user interface (Tablet) met my expectations	4.2 (2-7)
9. The E-scale reported my weight accurately	1.9 (1-5)
10. Once the E-Scale becomes more accurate and reliable, I would prefer to use the E-scale instead of other weight measuring devices I have previously used	5.8 (1-7)
System Usability Scale Score	69.2 (38-93)

4.3.5 Data from E-scale

After the E-scales were returned, the data that was stored on the Raspberry Pi computers were analyzed by applying the event detection algorithm from Chapter 3 to the stream of data that was saved. Plots of each of the subjects' data are shown in Appendix L. The accuracy and precision of the E-scales were recalculated based on the weights obtained from the event detection algorithm described in Chapter 3. These results are shown in Table 29. The accuracy was again calculated by the difference between baseline and final weights measured on the roll-on scale and the average of the first 3 and last 3 weights identified from the E-scale, respectively. The negative numbers mean that the E-Scale was measuring lower than the person's actual weight. Precision was calculated as the average distance each measurement was from the linear trendlines of that range

of data. Three subjects were chosen to include here to demonstrate the best, the middle, and the worst cases of the data. Those subjects' scatter plots (best: Subject 1, middle: Subject 6, and worst: Subject 7) are shown in Figure 29, Figure 30, and Figure 31, respectively.

Table 29: Accuracy and precision calculated from Event Detection algorithm

Subject	Baseline Accuracy (lbs.)	Final Accuracy (lbs.)	Precision
1	-68.3	-8.2	2.2
2	-26.7	-9.8	3.1
3	-22.9	-55.8	11.7
4	-31	-83.5	11
5	-31.9	-61.1	6.6
6	-56.5	-27.5	9.2
7	-86.5	-37.9	27.9
8	-	-	-
9	-11	-16.9	2.7
Average	**-41.9**	**-37.6**	**9.3**

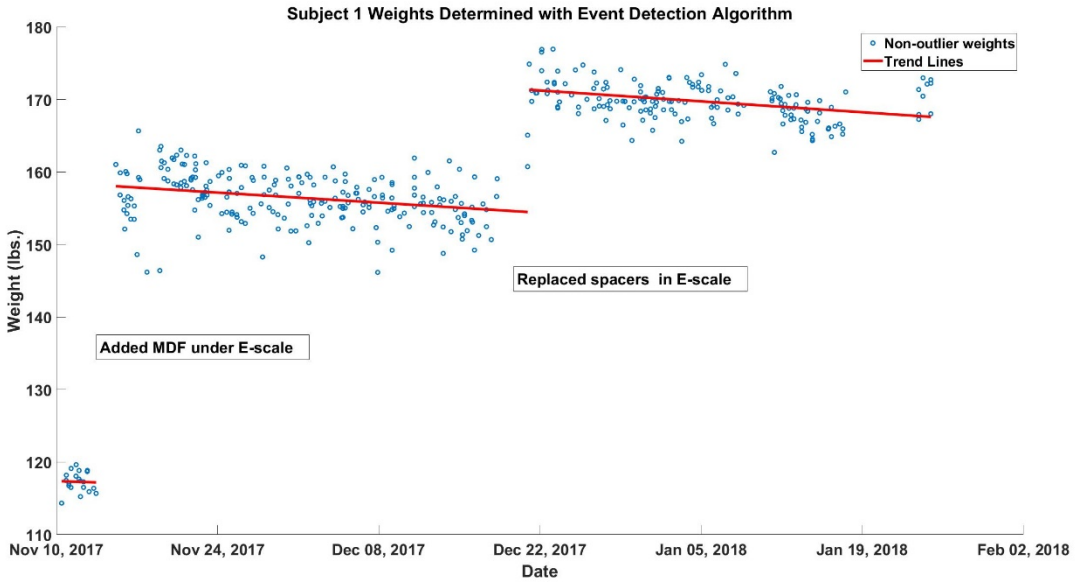


Figure 29: Scatter plot of weight vs. time of the subject with the most accurate data results.

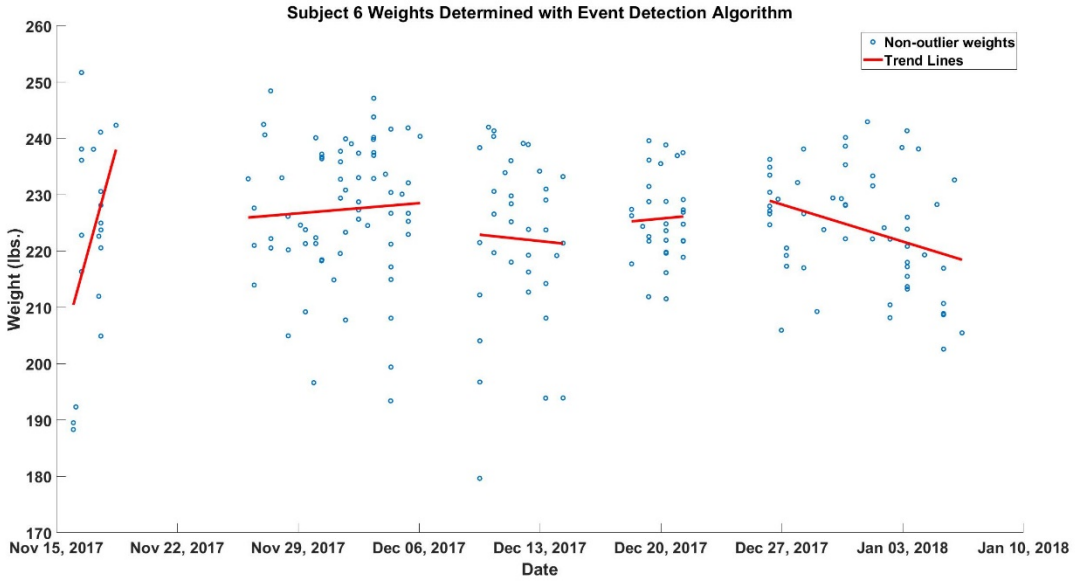


Figure 30: Scatter plot of weight vs. time of a subject with medium data results

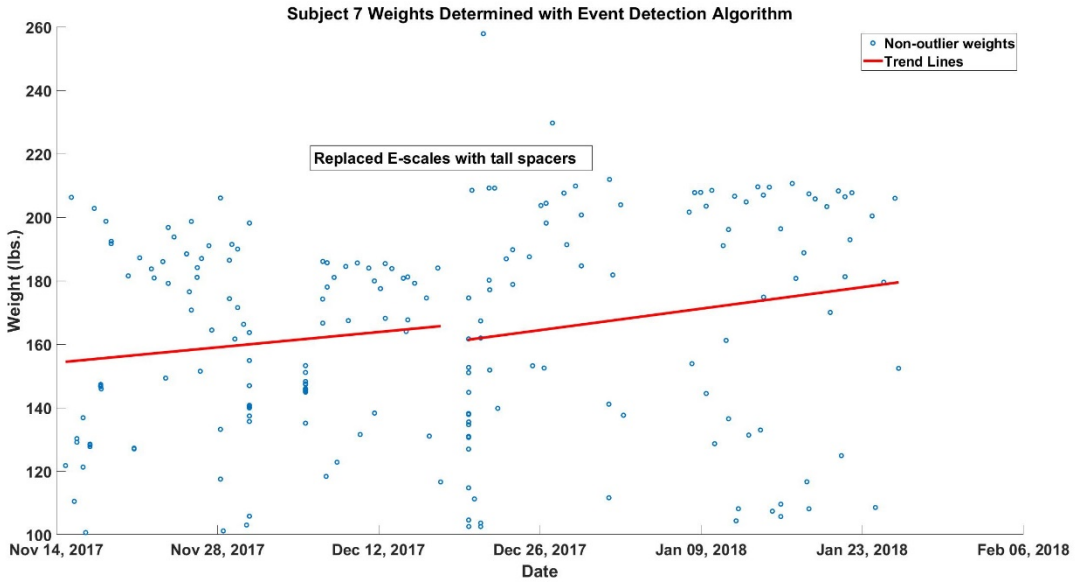


Figure 31: Scatter plot of weight vs. time of the subject with the least accurate data results

Data related to the number of bed exits and entrances and the time the person spent in bed were also investigated. Table 30 shows the data that were obtained from this analysis. The Sum of Weight Trends variable is calculated by summing the changes from beginning to end from all of the trendlines displayed on the Subject's figures in Appendix L. The Actual Change variable is the amount their weight changed throughout the study as measured from the roll-on scale (their weight change result).

Table 30: Data obtained from E-scales

Subject	Total time collecting (hrs.)	Total time in bed (hrs.)	Number of events	Number of non-outlier events	Percent of time in bed	Average time in bed at once (hrs.)	Sum of Weight trends (lbs.)	Actual Weight Change (lbs.)
1	1467.7	1065.1	442	403	72.6	4.82	-7.5	-5.8
2	550.5	290.6	184	134	52.8	3.16	-6.1	-7.6
3	1115.3	360.2	147	142	32.3	4.9	4.4	-3.6
4	1038.1	315.6	282	237	30.4	2.2	-11.8	6.7
5	1668.6	1100.3	2421	2309	66	0.95	-66.8	5.1
6	756.2	251	225	206	33	2.23	-8.6	-5.5
7	1326.8	226.7	204	198	17.1*	2.2	29.3	-15.5
8	No data							
9	1115.6	364.3	386	327	32.7	1.9	-9.8	-0.5

* By observing graphs of the data, it was evident that many of the bed exits were missed by the algorithm for this subject so those periods of the subject being in bed were ignored meaning this person was actually in bed more than this number suggests.

4.4 DISCUSSION

Although none of the changes in weight, abdominal girth, or body fat percentage were statistically significant at 0.05, on average all measures decreased during the course of this study. Two participants gained more than 5 lbs. which, for such a small sample, significantly affected the data.

Overall the participants were pleased with the program as 8 out of 9 of them answered 5 or higher on Question 5 of the final survey, a 7-point Likert scale question asking whether they were satisfied with the overall program, and all of them answered 5 or higher on Question 6 of the final survey, a 7-point Likert scale question asking whether they would recommend the program to other wheelchair users.

The retention for this study was above expectations as all of the participants finished the study. Compliance was also good as, except for one participant who did not use LoseIt! at all, only 3 weeks of journaling in LoseIt! were missed and the chat rooms were attended 74% of time.

While the average numbers for accuracy and precision seem much worse from data extracted from the E-scale by applying the event detection algorithm, there are some points of encouragement from these data and the graphs in Appendix L. Firstly, there are some outliers in the final accuracy and precision numbers which significantly impact the averages. Second, all of the accuracy numbers are showing that the E-scale is reading lower than the person's actual weight. This likely indicates that there is still some weight being transferred through the case or otherwise not recorded by the load cells in the subjects' homes that was not occurring in the lab when the E-scales were calibrated. Subjects 1, 2, and 7 had significant increases in the accuracy of their E-scales after some of the modifications were made, but the final accuracy numbers suggest there is still some work to be done to make them more accurate. For the participants whose E-scale accuracy got significantly worse throughout the study (Subjects 3, 4, and 5), it is believed that it had to do with the bed sliding off of the E-scales over time. The plots in Appendix L, show that Subject 3 had an abrupt drop off in weight about three-fourths of the way through the study while Subjects 4 and 5 weights decreased gradually over time.

The three plots (for Subjects 1, 6 and 7) in Figure 29, Figure 30, and Figure 31 show the best, middle, and worst examples of the data quality from the E-scale, respectively. Figure 29 portrays the improvements that occurred when adding medium density fiberboard under the E-scales and the taller spacers in the E-scale significantly increased the weight measurement. Although the weight measurement from the E-scale was still less than Subject 1's weight, the trend from the trendlines was close to the weight that subject actually lost signifying that it was sensitive to the weight being lost.

Figure 30, show that the trendline went down slightly for this subject, and this subject did actually lose weight during the study. However, there were several gaps where the scale was not working and the precision of the weight measurements was poor as they fluctuated several pounds above and below the trendline throughout the study.

Figure 31 shows the worst of the data. The precision for this subject was the worst and the range of measurements were scattered over more than 100lbs. The trendline for this subject shows that they gained weight, but in actuality this subject lost the most weight. The exact cause for why the weights varied so much with this participant is unknown, but it is assumed that the bed was shifting on top of the E-scales often and there may have been some issues with the electronics of this E-scale not reading consistently.

The data from the E-scales related to the number of events and time in bed are things which, to our knowledge, have never been studied or investigated. Assuming an average person would spend approximately 33% of their time in bed per day [82], it was found that 5 of our participants were relatively close to that number, while 3 spent more than 50% of their time in bed. However, there was no correlation between amount of weight lost and the time in bed as two of the three participants who spent over 50% of their time in bed lost the 2nd and 3rd most weight of our

participants while the other one gained weight. The same analysis was conducted on the 5 couples from Chapter 3 and all ten people were in bed less than 36% of the time. Typical sleep duration studies are self-report or conducted at a sleep lab, but these data demonstrate that the E-scale is a technology that could be used to further investigate these parameters objectively in people's homes. The E-scale can also be used with other furniture such as chairs or couches which could allow for calculations on behavior and sedentary analyses besides time in bed.

Another interesting result was the number of bed entry/exit events that were identified across the range of subjects. On average it was found that the participants got into or out of bed about 6 times a day (with the exception of Subject 5). That is similar to the number of events determined for the couples in Chapter 3 where each person got into or out of bed approximately 7.5 times a day. The average number of transfers the participants reported during the demographics questionnaire was 12 (also excluding Subject 5). Considering wheelchair users also perform transfers with vehicles, toilets, and other furniture, it is expected that the number of transfers that were recorded in bed to be less than what they reported that they do each day. Subject 5 was excluded because this subject had 5 times more events (bed exits and entrances) than the next highest subject. The demographic questionnaire where the subjects were asked how many transfers they do in a day showed that, instead of writing down a number, this subject just wrote "all day". This indicates that the E-scale is effective at detecting bed exits and entrances and highlights another area of research that could be explored.

During the study, a few of the participants actually found other ways to weigh themselves when their E-scales were not working correctly so they could check on their progress. This also demonstrates that there is a real need for the E-scale once it is a more accurate and reliable product. This population is looking for a device to use to monitor their weight.

4.4.1 Limitations

The timing for the study was likely a contributor to the low changes in weight as it went from November to February and overlapped the holiday season. A study in 2016 found that on average people in the United States generally gain about 1.3 lbs. during the Christmas-New Year's holiday season [83].

The results of the accuracy and precision of the E-scales did not support the hypotheses. During the course of the study, several technical issues were identified and solved that were noticed early after installation, but the underlying accuracy of the E-scale was a consistent challenge. The two main technical issues were the Bluetooth connection between the tablet and Raspberry Pi computer of the E-scale frequently disconnected which caused the participants to not be able to see their weight and the accuracy of the E-scale was not acceptable, especially for participants who had carpet under the E-scale. Changes were made to the E-scales for participants 1, 2, 5, and 7 which increased the accuracy of their E-scales, but accuracy is still lower than needed and does not meet specifications (described in Chapter 2). These two technical issues actually even led to difficulty in determining the actual accuracy and precision from their reported weights in LoseIt!, because either the E-scale app was not working so they could not see their weight, or the participants were frustrated with the inaccuracy of the E-scale so they chose to not use it. This explains why they only reported their weights 23% of the possible days. These issues and others as well as potential solutions are discussed in Section 2.4.4.

The accuracy and precision tests that were conducted also have limitations. When the participants' weight was measured at the baseline and final weigh-ins, they were fully dressed and may have had items in their pockets. That could have led to a small discrepancy between the weight that the E-scale measured when they were weighing at home in their beds. The precision test also

could have been affected by the time of day that they weighed themselves and the time between weighing. Since the participants only weighed themselves 23% of the possible days, there was an average of roughly 4 days between measurements, but in many cases, there were weeks between measurements. Further testing of accuracy and precision should be conducted in the lab once the technical issues in Section 2.4.4 are addressed.

The Bluetooth connection issues and accuracy of the E-scales also affected the usability results. When asked what issues they experienced with the E-scales, 8 of the 9 participants reported that it was not accurate and 7 of the 9 participants reported that the app frequently did not work. This can also be seen in Table 28 where the participants did not feel the E-scale reported their weight accurately. In contrast, the participants felt that if the E-scale became more accurate and reliable, they would prefer to use it over other available scales. The average score for the System Usability Scale (SUS) is 68, suggesting that with a score of 69.2 the E-scale is slightly more usable than an average system [84]. However, when looking at the answers to the 10 individual questions for the SUS (Appendix K), all of the questions had an average score above 2.4 except for question 6 ("I thought there was too much inconsistency in the system") which had and average score of 0.3. This highlights that a reliable screen and improvements in accuracy would make the system much more usable.

4.5 CONCLUSION

Although the weight, abdominal girth, and body fat percentage changes were not significant for this study, the trend was aligned with the hypothesis of the study. The participants had good retention and compliance with the study and also gave favorable feedback about the program.

Accuracy and precision and other reliability issues meant that the E-scales did not perform as expected, but several design issues were identified and addressed (described in detail in Section 2.4.4). Despite the technical issues, the participants felt that the E-Scale was highly usable and with improvements to the accuracy and reliability, they would use the device regularly.

5.0 FUTURE WORK AND OTHER APPLICATIONS

The customer discovery process in Chapter 1 identified a clear market need for wheelchair users to be able to weigh themselves in their homes. Several issues related to the functionality and cost of the E-scale were presented in Chapter 2 that need to be addressed before it is ready to be a commercial product. Algorithms were developed that could be used to allow the E-scale to identify and weight couples who share beds and filter out erroneous data callused by children and pets on the bed, or changes in the bedding that impact weight. A feasibility study was also conducted for the E-scale as part of a weight loss study where the desire for wheelchair users to have a way to monitor their weight was confirmed and the usability of the E-scale was tested. This chapter explores future work for the E-Scale, which includes use of the system for monitoring pressure injury risk (through pilot data that has been collected) and the possible next-steps to extend the activities described in Chapters 2, 3 and 4.

5.1 PRESSURE RISK ASSESSMENT AND PREVENTION COMPLIANCE PILOT STUDY

Based on the market feedback that was received on the importance of determining pressure ulcer risk and risk reduction intervention compliance, a pilot study was conducted to investigate the possibility of using the E-scale to identify and classify movements of a person on a bed.

Pressure ulcers are costly, dangerous, and mostly preventable complications that arise for various reasons in nursing facilities, hospitals and in the home. People with pressure ulcers in long-

term care facilities were more than twice as likely to die as those without pressure ulcers [85]. The average cost for treating a pressure ulcer is $38,000 [86] which equates to $11 billion annually to the US healthcare system [87]. The incidence of pressure ulcers varies across facilities, but studies have found that the incidence in intensive and progressive care units is 3.3% [88], in community-based nursing homes it is 5.1% (stage 2 and above) [89], and in VA Community Living Centers it is 4% [90]. Pressure ulcers normally occur over bony prominences that are in contact with beds and chairs with sore locations being indicative of the sore etiology. Ulcers on the back of the head, sacral area and back of the heel generally would be developed during periods where the person is laying on their back while ulcers on the ear, outsides of the shoulder, hip, knees and ankles generally would come from the person lying on their side. Ulcers on the Ischial Tuberosities, bottom of the heel, and balls of the feet would generally come from the person sitting up in a chair [91].

The Braden scale has been widely accepted as the gold standard to predict the risk of development of pressure ulcers because it is highly reliable. [88, 92-94]. It has six sub-scores, and each sub-score has four levels, except for Friction & Shear, which only has three levels. The score can range from 6 (highest risk) to 23 (lowest risk). To determine whether the predictive value can be improved, researchers have performed secondary analyses on Braden scale sub-scores and other patient-related factors. These studies have revealed that while all sub-scores are significant predictors of pressure ulcers, some are substantially more powerful than others [88, 95]. This work found that the strongest predictor, by far, is the friction & shear sub-score. Patients with a score of 1 on friction & shear were 126 times more likely to develop a pressure ulcer compared to those with a score of 3. Those with a score of 2 were 8 times more likely to develop a pressure ulcer than those with a score of 3. Similar hazard scores are noted with activity (4.25 times more likely with

a 1 vs. 3 or 4) and mobility (~3 times more likely with a 1 or 2 vs. 3 or 4) [88]. These three sub-scores are highlighted because they are all related to mobility and movement.

When risk for a pressure ulcer increases, typically signaled by a Braden score of < 18, a series of strategies are put in place to try to address and reduce that risk. The care plan is based on frequently updated clinical practice guidelines by the National Pressure Ulcer Advisory Panel (NPUAP). The most recent guidelines indicate four categories related to prevention: skin care, nutrition, repositioning and mobilization, and education [96]. The most intensive part of the prevention plan is related to repositioning and mobilization, because it often requires a clinician to turn the patient every two hours while in bed. Adherence with these prevention protocols is low, likely because they require intense effort of the already over-extended clinical staff. Studies, for instance, have indicated adherence ranging from 4.4% [97] to 41% [98]. Adherence related specifically to turning was estimated to be 32% [86] in a study of 835 patients in 35 of the VA's Community Living Centers. These low adherence rates put people at risk for preventable pressure injuries and should be addressed. A research team investigating the barriers to successful implementation of the pressure ulcer prevention guidelines published by the Joint Commission [99] list four recommendations to improve pressure injury prevention protocols. One is to observe turning practices and another is to provide a prompt to clinicians when patients should be turned.

The goal of this study was to evaluate the feasibility of using the E-Scale to support pressure injury prevention by determining whether E-Scale data can provide insight into when and what type of position changes occur for an individual in bed. This work extends the previous work described in Chapter 3 [52, 53] which classified large vs. small motions, by investigating whether E-Scale data can be used to identify position changes that are clinically known to be pressure relieving.

Methods: The E-scales were placed under a bed and 10 subjects (students and staff from our lab) were recruited into an IRB-approved study to complete a movement protocol on a bed with an E-Scale placed underneath the feet. The movement protocol included a total of 70 movements of a combination of rolling, turning in place, extremity movements, and assisted rolls with a 10 second rest period between movements. Table 31 shows the protocol.

Table 31: Pressure risk pilot study protocol

Movement	Description	Number and Timing
Rolling across the bed	90-degree turns (i.e. back to side)	15 movements with 10 seconds between
Turning in place (rotate while staying at the same location on the bed)	90-degree rotations (i.e. back to side)	15 movements with 10 seconds between
Extremity movements (move an arm or leg without changing position on bed or hip contact location	Movement of a single extremity (leg or arm)	15 movements with 10 seconds between
Assisted Roll (Lay still while assistant rolls you)	90-degree roll generated by an assistant (nurse)	10 movements with 10 seconds between
Random generated movements	Random set of 90 degree turns, 90-degree rotations in place, extremity movements and assisted rolls	15 movements with 10 seconds between

The data that were used from the E-scale for the algorithm development are listed in Table 32. These data all relate to a specific movement which is why there was the 10 second rest period between movements. Movements were defined in the data as consecutive periods where the total weight fluctuates more than 7 lb. over a 3 second window. Figure 32 shows a sample of two movements with the data identified.

Table 32: Data from E-scale for pressure risk pilot study

Data from each Movement	**Reason**
Weight standard deviation	Shows consistency of forces during movement (one smooth movement vs. many)
Time length of movement	Shows how long the movement lasted
Change in center of mass	How far did the center of mass change across the bed

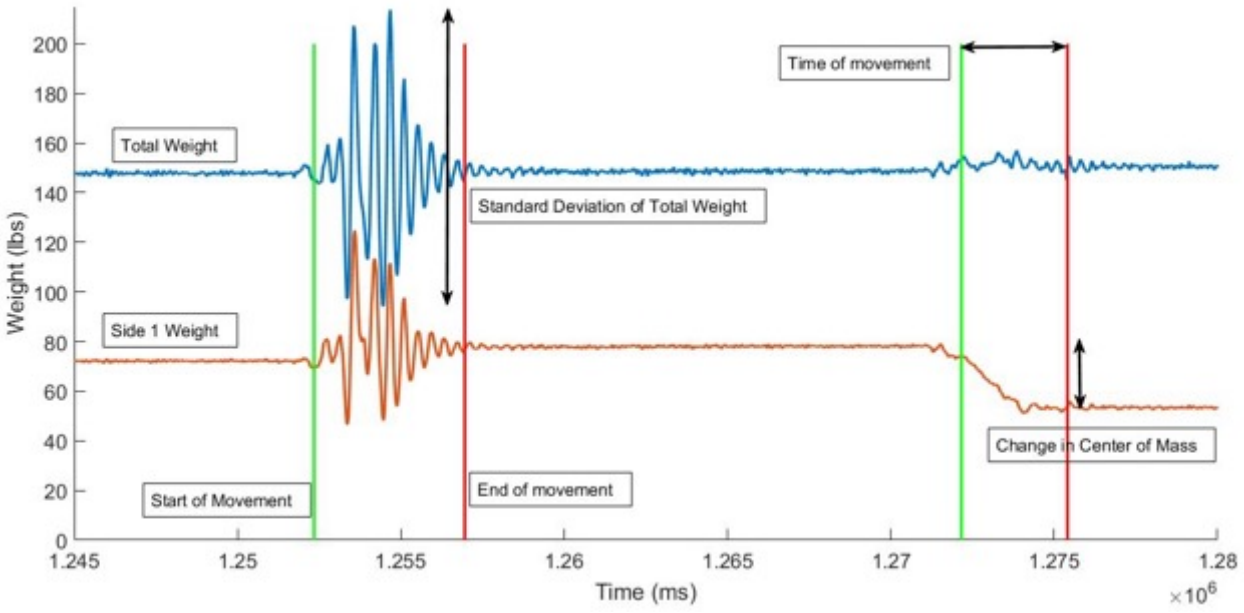


Figure 32: Plot of movements and data

A K-nearest neighbor approach [100] was used to evaluate the prediction algorithm. For the training set for the algorithm, a random selection of four movements from each of the first four segments of the movement protocol of each subject was used for a total of 160 data points (4 x 4 x 10). The accuracy of the algorithm was then evaluated with the other data points and the percentage of data points that were classified correctly was determined. It was hypothesized that the algorithm would be greater than 90% accurate.

The algorithm used the nearest 19 neighbors for each variable giving 57 total classification data points. The mathematical mode of those 57 points was then calculated to determine which classification that movement would be assigned. Since a random sample was selected as the training set, which would affect the accuracy, the analysis was completed 10 times with a different training sample each time. The average accuracy of those 10 trials was 82%. When the classifications were broken down by movement as shown in Table 33, it can be seen that the biggest errors occur with the rolls and assisted rolls being classified as each other incorrectly. Figure 33 shows a scatter plot of the deviation and center of mass variables of the 4 different movements where it can also be seen that the rolls and assisted rolls overlap the most. Further analysis could be investigated to find better ways of distinguishing between those two movements which could increase the overall accuracy further. In addition, distinguishing between all 4 of these movements may not be needed for all situations or markets. For instance, it may only be important to distinguish between pressure relieving movements and non-pressure relieving movements which would improve accuracy. If the rolls, turns and assisted rolls are combined as pressure relieving movements and extremity movements are considered as non-pressure relieving movements, then the accuracy of the analysis would be higher than 87%.

Table 33: Classification results by movements

	Classified as movement			
Actual Movement	Roll	Turn	Extremity	Assisted
Roll	74%	3%	8%	15%
Turn	0%	99%	0%	1%
Extremity	4%	7%	87%	2%
Assisted	27%	11%	4%	58%

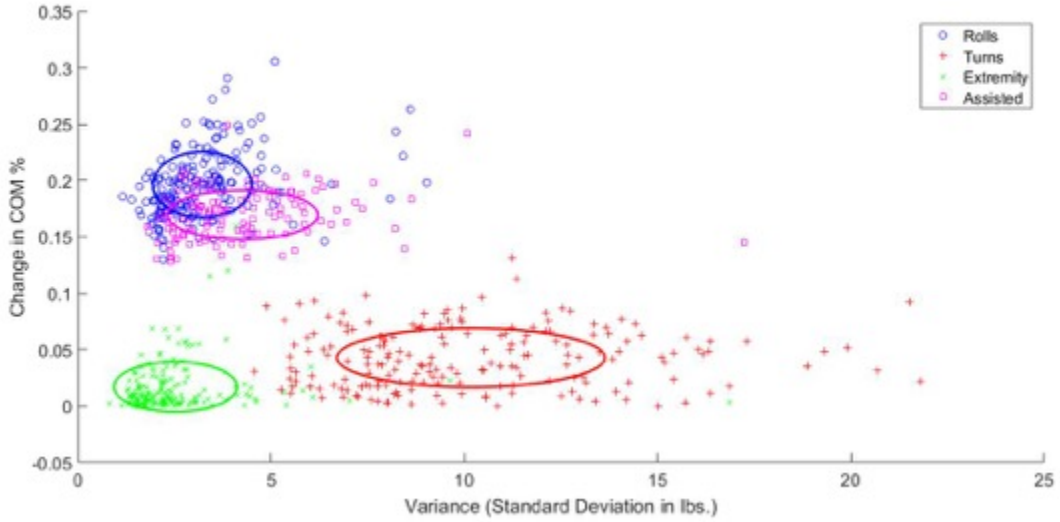


Figure 33: Scatter plot of movements

5.2 FUTURE WORK

In order to further the technology readiness of the E-scale as shown in Table 7 and reproduced here as Table 34, the E-scale requires significant design changes to address the design deficiencies identified through our in-lab and in-home testing. Several studies will also need to be completed that are described below.

Table 34: E-scale functions and technology readiness

TECHNOLOGY READINESS LEVEL:	Ideation	Research	Proof of Concept	Prototype	Pre-Production	Mass Produced	Commercialized
Core Technology							
C1: Hardware (Sensors)	Ch. 1				Ch. 3		
C2: Software (E-Scale Data Collection)	Ch. 1				Ch. 2,3,4		
Data Analysis Modules							
M1: Weight Feedback	Ch. 1				Ch. 2,3		
M2: Multi-person Decoding	Ch. 2				Future work		
M3: Pressure Injury Risk	Ch. 4				Future work		
M4: Sleep Quality	Future work						
M5: Predictive Bed Exit (fall risk)	Future work						

5.2.1 Core Technology

Version 3 of the E-scale will need significant improvements as outlined in Section 2.4.4. After that redesign, the system should be rigorously tested in the lab similarly to how Version 1 of the E-scale was tested in Section 2.2.2 and including the improvements to the testing process described in Section 2.6. It should also include some testing to see how the weight is affected by the load (from the bed leg) being shifted on each of the individual E-scales. After this testing, it should again be tested with actual users similarly to the weight loss study presented in Chapter 4. After successful numbers are achieved in all of these tests, there would be confidence that it would perform well for people who would be purchasing it. The redesign should also incorporate some of the cost reduction suggestions and designs discussed in Section 2.5 so that the price point would be closer to or achieve the goal of $200 for the system.

5.2.2 Weight Feedback

After the E-scale is ready for the market, the next step in this line of research should be to conduct additional effectiveness studies in the community. Another group study that is sufficiently powered on the usefulness of the E-scale for weight loss for wheelchair users should be completed. Ideally it would involve multiple sites and a control group that does not have the E-scale while the intervention group does have the E-scale. Having the E-scale be an independent variable will allow for measuring the effect of the E-scale on weight loss. A larger controlled study will provide efficacy data on the use of the E-scale as an intervention component for weight loss.

5.2.3 Multi-person Decoding

The next step in this line of research would be to complete another study with couples who are using the E-scale with the event detection and classification algorithms presented in Chapter 3 incorporated in the E-scale. This study should evaluate how well the E-scale could track their weight for a period of time. The participants should weigh themselves daily with another scale that can be used as ground-truth. Then the outcomes of this study should investigate how many weight measurements from the E-scale were recorded from each person during the trial and how accurate those weight measurements were compared with the other scale. There should also be some subjective feedback about how well they thought the E-scale performed and how useful they feel the passive weight monitoring functionality would be for their use.

5.2.4 Pressure Injury Risk

In the pressure injury risk assessment line of research, another small study should be conducted to look at natural movements as opposed to having a set of prescribed motions. This would likely be done in a sleep lab and/or in a nursing home where the room could be video recorded while the participant is in bed. The movements would have to be classified by having an independent observer watch the video recording and classify the movements that are occurring. Then the algorithm, which was developed, could be applied to that data or a new algorithm could be developed. Then an effectiveness study should be implemented in multiple nursing home facilities to see what the effect of using the E-scale is on compliance with turning protocols and on the incidence of pressure injuries in facilities that utilize the E-scale.

5.2.5 Sleep Quality and Predictive Bed Exits

Analysis techniques for sleep quality and predictive bed exits should also be explored. These could likely be completed during the other studies which have been proposed for the pressure injury risk assessment. During a study in a sleep lab, there would be ground truth data about sleep quality from the polysomnogram. Statistics for how well a sleep quality algorithm for the E-scale could predict periods of sleep should be determined. Predictive bed exit is an assumption that using the E-scale data, not only could a bed exit be detected, but a person's intent to exit the bed could be identified before it actually occurs by finding some indicative movements. For this algorithm development, data from Chapter 3 could be explored to determine whether characteristic movements that occur before a person exits a bed can be identified. However, these data are from able-bodied individuals who may have different movement characteristics than people who are at

risk for falling. The E-scale was also only recording at approximately 1 Hz for the study in Chapter 3. Most activity monitors and the E-scale used for the movement classification study at the beginning of this chapter, record at at least 30 Hz.

The ideal data for this algorithm development could be data collected from the study in the nursing home with residents who are at risk for falls but could actually get out of bed independently. The times where any of the participants exited the bed would be identified and algorithms would have to be explored to determine if there is a way to identify if the movement in the bed before these events differed from other movements in some way. If they could be differentiated, then the amount of time between when the algorithm detected a likely bed exit and the time that the bed exit occurred would need to be calculated so that the amount of warning time that the E-scale could provide the staff could be determined.

6.0 CONCLUSION

Development of the E-Scale was motivated by the high prevalence of obesity among wheelchair users, and the lack of available technology for them to monitor their weight. Chapter 2 describes 4 versions of the E-scale and how their designs were changed and how they were tested. In Chapter 3, algorithms were developed that enable a bed scale such as the E-scale to passively monitor the weight of individuals who share a bed. While the accuracy of these algorithms was less than hypothesized, with improved accuracy of the E-scale they nevertheless can effectively track the weight trends and other motion characteristics of individuals who share a bed. In Chapter 4, the results of a 3-month weight loss study where the participants were asked to use the E-scale daily to monitor their weight were presented. Although the participants, on average, lost weight, reduced their abdominal girth and reduced their body fat percentage, none were statistically significant. The accuracy and precision of the E-scales, as well as the operability of the user interface during this study, were poor enough that many of the participants did not use the E-scales consistently during this study. However, the results of the System Usability Scale and the final survey show that many would like to use the E-scale once the technical issues are resolved. In Chapter 5, some pilot data for movement detection and classification algorithms that could be used to measure pressure injury risk were presented. Lastly, the next steps in the E-scale line of research were presented.

The studies described in this dissertation advanced the readiness of the E-scale technology to be commercially available on the market. While the hypotheses for the studies were not fully supported, new and significant achievements were made in the areas of the E-Scale design & Development (Chapter 2), the development of algorithms to identify the occupant of a bed

(Chapter 3) so that the weight of multiple individuals can be tracked, the feasibility of the E-Scale in a standardized weight loss intervention (Chapter 4) and the use of the E-Scale to characterize whether pressure reliving motions have occurred (Chapter 5). In addition, we describe potential next-steps for this work (Chapter 5).

APPENDIX A

PLOTS FROM COUPLE STUDY

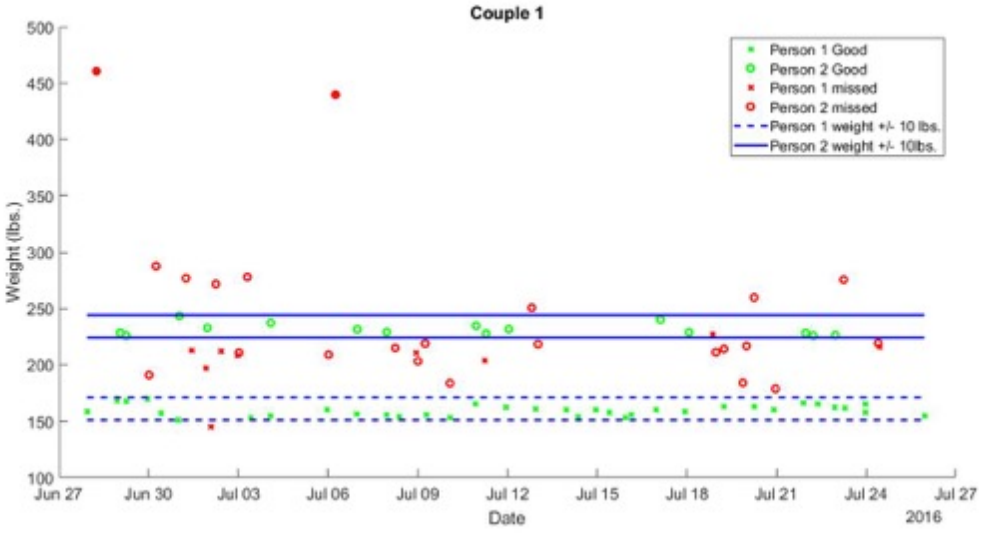


Figure 34: Couple 1 data

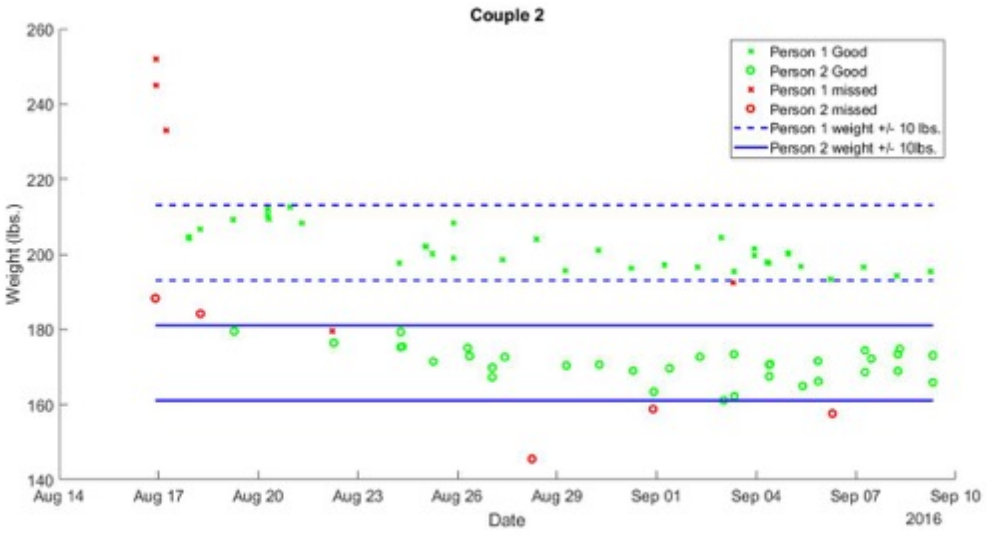


Figure 35: Couple 2 data

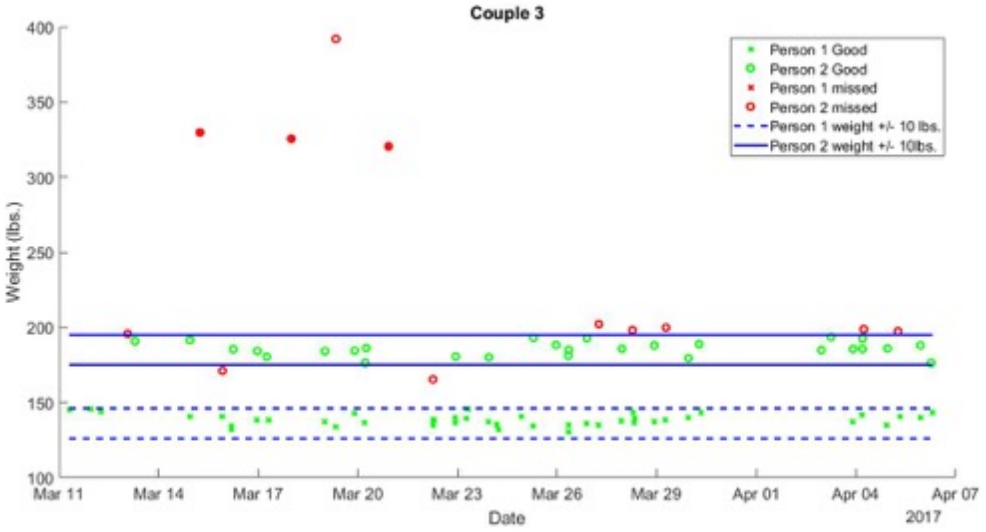


Figure 36: Couple 3 data

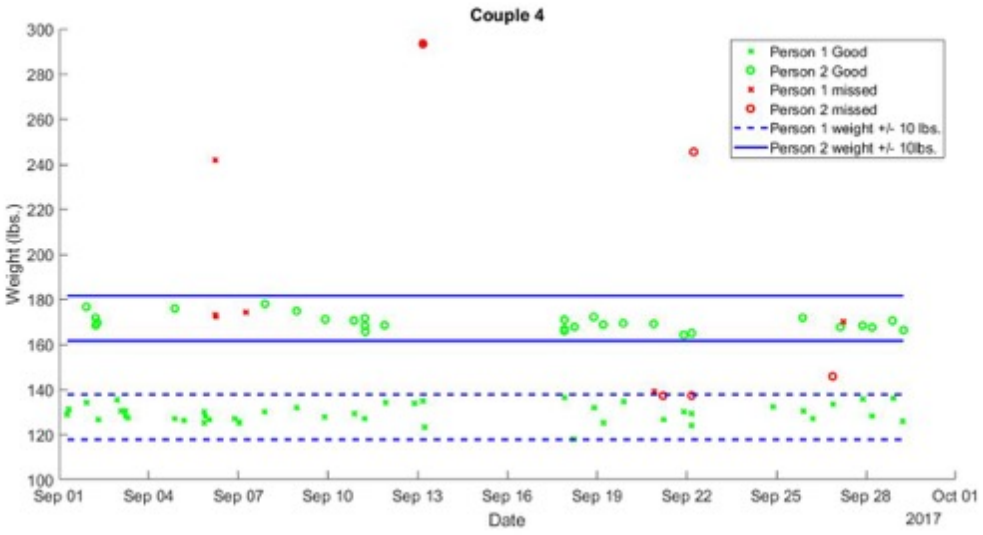


Figure 37: Couple 4 data

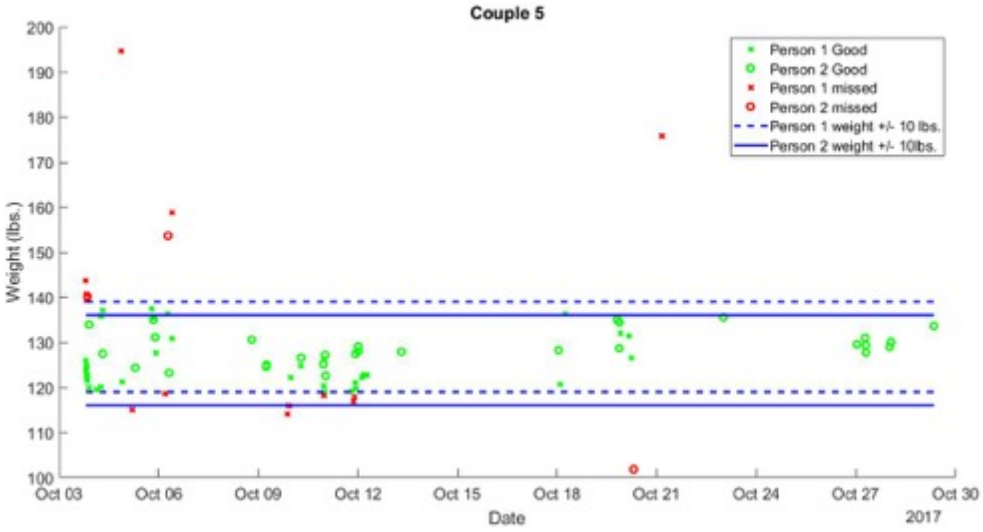


Figure 38: Couple 5 data

APPENDIX B

SCREENING TOOL

The participant will be asked if it is okay that we go through a series of questions to determine if they are eligible for the study, and instructed that they may discontinue and choose not to answer at any time.

Phone Screen Interview
Screening:

1. Gender: ☐Male ☐Female

2. Age: ____ **(18-80)**

3. Current Weight: _____pounds

4. Current Height: _____inches

Office Use: BMI = _____ (≥27.0 and ≤40.0 kg/m2) (weight(lbs.)/(height(in)^2)*703

5. Do you use a wheelchair as your primary means of mobility? (≥40 hrs/week)
☐ **YES** ☐ NO

6. Does your bed have 4 legs?
☐ **YES** ☐ NO

7. Do you have access to a wifi network at your home?
☐ **YES** ☐ NO

8. Do you currently use an android device or would you be willing to use one provided to you for the purposes of this study?
☐ **YES** ☐ NO

9. Do you plan to spend any time out of town on vacation or business in the next 13 weeks that may affect your ability to participate in the study?
☐ YES ☐ **NO** If "yes", specify: _____

10. Do you plan on relocating outside of the Greater Pittsburgh Area within the next 13 weeks?
☐ YES ☐ **NO** If "yes", specify: _____

11. Have you ever been told by a doctor or other medical person that you have any of the following conditions?
Heart Disease, Angina, Hypertension, Heart Attack, Stroke, Diabetes, Cancer, Myocardial Infarction, Asthma, Congestive Heart Failure
☐ YES ☐ **NO**

12. Are you being treated or taking any prescription medications for depression or anxiety?
☐ YES ☐ **NO**

13. Are you currently being treated for an eating disorder?
☐ YES ☐ **NO**

14. Are you taking any medications for the purpose of weight loss?
☐ YES ☐ **NO** If "yes", specify: _____

15. Are you taking any medications that may not be intended for weight loss, but you have noticed that the medication may affect your body weight?
☐ YES ☐ **NO** If "yes", specify: _____

16. Do you consume more than 4 alcoholic drinks/day?
☐ YES ☐ **NO**

17. Are you currently a member of another organized exercise or are you participating in an organized weight reduction program?
☐ YES ☐ **NO** If "yes", specify: _____

18. Have you lost weight in the past 3 months?
☐ YES ☐ **NO** If "yes", specify number of pounds:_____ Method used:_____
Note: Ineligible if weight loss is ≥5% of current body weight or 15 pounds total

19. Have you undergone bariatric surgery (lap-band, gastric bypass, etc.)?
☐ YES ☐ **NO**

WOMEN ONLY COMPLETE THE FOLLOWING QUESTIONS
20. Are you currently pregnant, have you been pregnant in the last 6 months, or do you plan on becoming pregnant in the next 13 weeks?
☐ YES ☐ **NO**

*If all criteria are met:

I believe you qualify for this study. If you would like to proceed, we will need you to contact your doctor for a letter saying that it is ok for you to participate in a weight loss study. If your doctor needs more information, you can inform him/her that it is a standard behavioral

treatment weight loss intervention that has been adapted for people with mobility impairments where the goal will be to lose approximately 5% of your weight over the 13-week period. He/She can also contact the study team at 412-822-3700 and ask for Jonathan Duvall. Once you receive the letter, we will schedule a time for you to come to our lab where we will go through the consent process to enroll you in the study.

**If all criteria are not met:

Based on your answers, I don't believe you will qualify for this study. I want to thank you for your time and your willingness to assist with our study.

APPENDIX C

CENTER FOR EPIDEMIOLOGIC STUDIES DEPRESSION SCALE (CES-D)

Below is a list of the ways you might have felt or behaved. Please tell me how often you have felt this way during the past week.

During the Past Week	Rarely or none of the time (less than 1 day)	Some or a little of the time (1-2 days)	Occasionally or a moderate amount of time (3-4 days)	Most or all of the time (5-7 days)
1. I was bothered by things that usually don't bother me.	☐	☐	☐	☐
2. I did not feel like eating; my appetite was poor.	☐	☐	☐	☐
3. I felt that I could not shake off the blues even with the help from my family or friends.	☐	☐	☐	☐
4. I felt I was just as good as other people.	☐	☐	☐	☐
5. I had trouble keeping my mind on what I was doing.	☐	☐	☐	☐
6. I felt depressed.	☐	☐	☐	☐
7. I felt that everything I did was an effort.	☐	☐	☐	☐
8. I felt hopeful about the future.	☐	☐	☐	☐
9. I thought my life had been a failure.	☐	☐	☐	☐
10. I felt fearful.	☐	☐	☐	☐
11. My sleep was restless.	☐	☐	☐	☐
12. I was happy.	☐	☐	☐	☐
13. I talked less than usual.	☐	☐	☐	☐
14. I felt lonely.	☐	☐	☐	☐
15. People were unfriendly.	☐	☐	☐	☐
16. I enjoyed life.	☐	☐	☐	☐

17. I had crying spells	☐	☐	☐	☐
18. I felt sad.	☐	☐	☐	☐
19. I felt that people dislike me.	☐	☐	☐	☐
20. I could not get going.	☐	☐	☐	☐

Scoring (Not to be shared with potential subjects):
Zero for answers in the first column, 1 for answers in the second column, 2 for answers in the third column, 3 for answers in the fourth column. The scoring of positive items (4,8,12,16) is reversed. Possible range of scores is zero to 60, with the higher scores indicating the presence of more symptomatology. A score of 20 or greater means the potential subject is ineligible and should be given resources for depression.

APPENDIX D

EATING DISORDER DIAGNOSIS SCALE (EDDS)

Eating Disorder Diagnostic Scale

Please carefully complete all questions.

Over the past 3 months…	Not at all		Slightly		Moderately		Extremely
1. Have you felt fat?	1	2	3	4	5	6	7
2. Have you had a definite fear that you might gain weight or become fat?	1	2	3	4	5	6	7
3. Has your weight influenced how you think about (judge) yourself as a person?	1	2	3	4	5	6	7
4. Has your shape influenced how you think about (judge) yourself as a person?	1	2	3	4	5	6	7

5. During the past 6 months have there been times when you felt you have eaten what other people would regard as an unusually large amount of food (e.g. a quart of ice cream) given the circumstance? YES NO

6. During the times when you ate an unusually large amount of food, did you experience a loss of control (feel you couldn't stop eating or control what or how much you were eating)? YES NO

7. How many DAYS per week on average over the past 6 MONTHS have you eaten an unusually large amount of food and experienced a loss of control? 0 1 2 3 4 5 6 7

8. How many TIMES per week on average over the past 3 MONTHS have you eaten an unusually large amount of food and experienced a loss of control? 0 1 2 3 4 5 6 7
8 9 10 11 12 13 14

During these episodes of overeating and loss of control did you…

9. Eat much more rapidly than normal? YES NO
10. Eat until you felt uncomfortably full? YES NO
11. Ear large amounts of food when you didn't feel physically hungry? YES NO
12. Eat alone because you were embarrassed by how much you were eating? YES NO
13. Feel disgusted with yourself, depressed, or very guilty after overeating? YES NO
14. Feel very upset about your uncontrollable overeating or resulting weight gain? YES NO

15. How many times per week on average over the past 3 months have you made yourself vomit to prevent weight gain or counteract the effects of eating? 0 1 2 3 4 5 6 7
8 9 10 11 12 13 14

16. How many times per week on average over the past 3 months have you used laxatives or diuretics to prevent weight gain or counteract the effects of eating? 0 1 2 3 4 5 6
7 8 9 10 11 12 13 14

17. How many times per week on average over the past 3 months have you fasted (skipped at least 2 meals in a row) to prevent weight gain or counteract the effects of eating? 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

18. How many times per week on average over the past 3 months have you engaged in excessive exercise specifically to counteract the effects of overeating episodes? 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

19. How much do you weigh? If uncertain, please give your best estimate_____lb.

20. How tall are you? _____ft _____in

21. Over the past 3 months, how many menstrual periods have you missed? 1 2 3 4 N/A

22. Have you been taking birth control pills during the past 3 months? YES NO

Scoring (Not to be shown to subjects)

A diagnosis of DSM-1V anorexia nervosa is made if an individual reports (a) height and weight data on EDDS Items 19 and 20 that result in a body mass index (BMI = Kg/M^2) of less than 17.5, (b) a fear of weight gain or becoming fat as indexed by a score of 4 or greater on EDDE Item 2, (c) undue influence of body weight or shape on self-evaluation as indexed by a score of 4 or greater on either EDDS Item 3 or 4, and (d) amenorrhea in postmenarcheal females as indexed by a 3 on EDDS Item 21. Following the EDE scoring algorithm, if an individual meets the first and fourth criteria above, it is not necessary for the individual to endorse the second and third criteria. Further, because oral contraceptives can result in a regular menstrual cycle, to be on the conservative side, participants who were taking oral contraceptives that met the low weight criteria were coded as amenorrheic. This approach is also used in the EDE.

A diagnosis of DSM-IV bulimia nervosa is made if an individual reports (a) regular eating binges marked by a perceived loss of control and the consumption of a large amount of food as indexed by a response of yes to EDDS Item 5, a yes to EDDS Item 6, and a response of greater than 2 on EDDS Item 8; (b) regular use of compensatory behaviors as indexed by a response of 8 or greater on the sum of EDDS Items 15, 16, 17, and 18; and (c) undue influence of body weight or shape on self-evaluation as indexed by a score of 4 or greater on either EDDS Item 3 or 4.

A diagnosis of DSM-IV binge-eating disorder is made if an individual reports (a) regular eating binges marked by a perceived loss of control and the consumption of a large amount of food as indexed by a response of yes to EDDS Item 5, a yes to EDDS Item 6, and a response of greater than 2 on EDDS Item 7; (b) an endorsement of at least three of the features that may be associated with binge eating as indexed by ayes response to at least three of the features described in EDDS Items 9, 10, 11, 12, and 13; (c) marked distress regarding binge eating as indexed by a yes response to EDDS Item 14; and (d) the absence of any compensatory behaviors as reflected by a 0 response to EDDS Items 15, 16, 17, and 18.

If any of these 3 criteria are met, the subject is ineligible and should be given resources for eating disorders.

APPENDIX E

LIST OF WEEKLY TOPICS

Week 1: Welcome to the Group Lifestyle Balance Program (GLB)

Week 2: Be a Fat and Calorie Detective

Week 3: Healthy Eating

Week 4: Move those Muscles

Week 5: Tip the Calorie Balance

Week 6: Get Comfortable in the Kitchen

Week 7: Take Charge of What's Around You

Week 8: Problem Solving

Week 9: Four Keys to Healthy Eating Out

Week 10: The Slippery Slope of Lifestyle Change

Week 11: Stress and Time Management

Week 12: Looking Back and Looking Forward

APPENDIX F

FINAL QUESTIONNAIRE

Please rate the following components of the weight loss intervention according to your satisfaction, and how helpful you feel like it was to achieving your weight-loss goal:

1. Educational Materials:

Extremely Dissatisfied						Extremely Satisfied
1	2	3	4	5	6	7

Extremely Unhelpful						Extremely Helpful
1	2	3	4	5	6	7

2. Online Meetings:

Extremely Dissatisfied						Extremely Satisfied
1	2	3	4	5	6	7

Extremely Unhelpful						Extremely Helpful
1	2	3	4	5	6	7

3. LoseIt! Journals:

Extremely Dissatisfied						Extremely Satisfied
1	2	3	4	5	6	7

Extremely Unhelpful						Extremely Helpful
1	2	3	4	5	6	7

4. E-scale:

Extremely Dissatisfied						Extremely Satisfied
1	2	3	4	5	6	7

Extremely Unhelpful						Extremely Helpful
1	2	3	4	5	6	7

5. How satisfied were you with the overall program?

Extremely Dissatisfied						Extremely Satisfied
1	2	3	4	5	6	7

6. How likely is it that you would recommend the program to other wheelchair users?

Extremely Unlikely						Extremely Likely
1	2	3	4	5	6	7

7. How many of the 12 weekly lessons did you read fully?

none	1-2	3-5	6-8	9-11	All

Please answer the following questions specifically for the E-scale:

8. The E-scale was easy to use:

Completely Disagree						Completely Agree
1	2	3	4	5	6	7

9. The E-scale user interface (Tablet) met my expectations:

Completely Disagree						Completely Agree
1	2	3	4	5	6	7

10. The E-scale reported my weight accurately:

Completely Disagree						Completely Agree
1	2	3	4	5	6	7

11. Once the E-Scale becomes more accurate and reliable, I would prefer to use the E-scale instead of other weight measuring devices I have previously used:

Completely Disagree						Completely Agree
1	2	3	4	5	6	7

Please list other weight measuring devices you have used.

_____

Once the E-Scale is updated so that it is reliable and accurate, I would use it to monitor my weight in my home?

Completely Disagree						Completely Agree
1	2	3	4	5	6	7

What, if any, issues did you have with using the E-scale? (choose all that apply)

□ Not Accurate

□ Tablet frequently did not work

□ Bed was unstable on the E-scale

□ Bed height on the E-scale caused issues transferring

□ Frequently hit the scales with wheelchair or feet

□ Other (please explain below)

_____

_____

_____

If you could change something about the E-scale what would it be?

_____

_____

_____

Please indicate how likely it is that you would purchase the E-scale (fully functional and accurate) if it costs…

$200	1 Very Unlikely	2	3	4	5	6	7 Very Likely
$400	1 Very Unlikely	2	3	4	5	6	7 Very Likely
$600	1 Very Unlikely	2	3	4	5	6	7 Very Likely

Please add any additional comments about any aspects of the study.

_____

_____

_____

_____

_____

_____

APPENDIX G

SYSTEM USABILITY SCALE

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

Scoring SUS

SUS yields a single number representing a composite measure of the overall usability of the system being studied. Note that scores for individual items are not meaningful on their own.

To calculate the SUS score, first sum the score contributions from each item. Each item's score contribution will range from 0 to 4. For items 1,3,5,7,and 9 the score contribution is the scale position minus 1. For items 2,4,6,8 and 10, the contribution is 5 minus the scale position. Multiply the sum of the scores by 2.5 to obtain the overall value of SU.

SUS scores have a range of 0 to 100.

APPENDIX H

DEMOGRAPHICS QUESTIONNAIRE ANSWERS

Table 35: Demographics

Subject	1	2	3	4	5	6	7	8	9
Age	68	38	32	36	55	56	70	28	56
Gender	Female	Female	Male	Male	Female	Male	Male	Male	Female
Height (in.)	59	64	71	73	64	71	69	53	53
Weight (lbs.)	185	177.5	234.6	217	172.3	246.6	232.7	137.9	160.3
BMI	37.4	30.5	32.7	28.6	29.6	34.4	34.4	34.5	40.1
SRAHP score	80	97	83	85	94	98	83	91	104
CES-D score	9	9	2	3	9	2	1	1	7
Abdominal Girth (in.)	48	39.5	45.5	44	39.5	45.5	56.5	39	48
Body-fat Index	49.7	33	24.1	16.5	36.2	34.6	Unable	28.9	43.3
Race 1=Black or African American 3=White or Caucasian	3	3	3	3	1	3	3	3	3
Highest Education 1=High School/GED 2=Some College 3=Associates Degree 4=Bachelor's Degree 5=Master's Degree	4	2	5	3	2	4	4	1	4
Employment 1=Unemployed 2=Part-time 3=Full-time 4=Retired	4	2	3	1	1	3	2	2	3
Annual Household Income 1=<$10k 2=$10-20k 3=$20-30k 4=$30-40k 5=$40-50k 6=>$50k 7=No Answer	7	3	6	4	2	6	3	1	6

Table 35 (continued)

Start date for wheelchair use	1963	2007	2011	2001	2008	2013	1997	1995	1986
Type of Wheelchair 1=Manual 2=Power	2	1	1	1	1	1	2	2	2
Brand 1=Action/Invacare 3=Permobil 4=Sunrise/Quickie 9=Tilite	3	4	9	4	1	9	1	3	3
Model	C300	2Lite	Aero 2	Q7	A4	-	tdx	-	F500
Able to walk	No	Yes	No	No	No	Yes	No	No	No
How far at one time 1=Around the house 2=About 1 block	-	1	-	-	-	2	-	-	-
Wheelchair for outdoor use only?	No	No	-	-	No	-	-	-	-
Hrs./day in wheelchair	6-12	12-24	12-24	6-12	12-24	6-12	12-24	6-12	12-24
Time moving chair	4 hrs.	1-2 hrs.	1-2 hrs.	5+ hrs.	All day	10-30 min.	5-6 hrs.	1-2 hrs.	5 hrs.
Time working at desk	2 hrs.	5 hrs.	7 hrs.	3 hrs.	0	8 hrs.	6 hrs.		1 hrs.
Time working at computer	3 hrs.	5 hrs.	7 hrs.	3 hrs.	0	8 hrs.	6 hrs.		5 hrs.
Time with arms overhead	0	20 min	15 min	1 hrs.	0	0	0		0
Time working with hands	5 hrs.	6 hrs.	1 hrs.	6 hrs.	0	8 hrs.	6 hrs.		1 hrs.
Time driving	0	30 min	3 hrs.	1-2 hrs.	0	2 hrs.	0		2 hrs.
Time reading	0	1 hrs.	10 min	3 hrs.	0	8 hrs.	6 hrs.		1 hrs.
# of transfer per day	6	15	12	16	all day	12	3	6	26
Days per week leaving home	5	5	7	6	7	7	6	4	7
Distance moving per day 1=<300 ft 2=300-3,000 ft 3=3,000-5,000 ft 4=5,000-10,000 ft 5=10,000-25,000 ft 6=>25,000 ft	4	3	3	4	3	4	6	1	6
Date of injury/diagnosis	1949	1998	2011	2001	2008	2012	1966		1986

Table 35 (continued)

Condition **1=Spinal Cord Injury** **7=Muscular Dystrophy** **10=Spina Bifida** **11=Stoke** **12=Post-polio syndrome** **13=Transverse Myelitis**	12	7, 13	1	1	1	11	7	1, 10	1
Confounding conditions **1=Arthritis** **2=Asthma** **3=Cancer** **5=Diabetes** **8=Thyroid** **11=High Blood Pressure** **12=None**	2, 5, 11	8, 11	12	12	11	12	3, 11	12	1, 11
Other conditions **1=Scoliosis** **5=Fibromyalgia** **6=None**	5	6	6	6	6	6	6	1	1
Difficult to maintain healthy weight/why? **1=No** **2=Unable to exercise** **3=No time for gym** **4=No accessible equipment** **5=Don't eat healthy food** **6=Can't monitor weight** **7=Other**	4,5,6	3,6	2,3	4,6	1	7	2,4,5,6	5	2,5
How do you weigh yourself? **1=Scale at home** **2=Doctor's office** **3=Other**	None	1	2	3: WC at wife's work	None	2	2	2	2
How long ago did you last weigh? **1=This week** **2=A week ago** **3=Two weeks ago** **4=A month ago** **5=3 months ago** **6=6 months ago** **7=A year ago**	4	4	6	4	1	1	6	7	7

Table 35 (continued)

Doctor check weight at every visit? How often? 1=No 2=Yes	1: yearly	1	1: 6 mon	1	2: 6 mon	2: 6 mon	1	1: 3x/year	1: 6 mon
Weighing equipment at home? 1=Stand on scale 5=None	5	1	5	1	5	1		5	
Would you like weight monitoring? 1=No 2=Yes	2	2	2	2	1	2	2	1	1
How much would you pay for weight monitoring?	$50	$200	$100	$100	-	?	$10	-	-
Been enrolled in weight loss program before? 1=No 2=Weight watchers 7=Apps	1	2, 7	1	1	1	1	2	1	1
Goals for next 3 months? 1=Lose Weight	1	1	1	1	1	1	1	1	1
I would like to measure my weight independently (without any assistance) on a scale.*	1	1	1	1	5	5	5	2	5
I would prefer to measure my weight in my home rather than primary care.*	1	1	1	1	5	5	2	1	3
I would like to use an accessible technology to enhance my weight management.*	1	1	2	2	5	5	1	2	2
I would like my insurance provider to sponsor a weight scale for me.*	1	1	1	1	5	5	2	1	2
I would feel motivated to maintain weight with regular weight tracking.*	1	1	2	1	5	2	1	2	5

Table 35 (continued)

I feel weight management technology does not help in taking control of own health.*	2	3	3	4	5	3	4	5	5

* 1=Strongly Agree, 2=Somewhat Agree, 3=Somewhat Disagree, 4=Strongly Disagree, 5=No Opinion

APPENDIX I

MEASUREMENT CHANGES

Table 36: Measurement changes during weight loss study

Subject	1	2	3	4	5	6	7	8	9
Initial weight (lbs.)	185	177.5	234.6	217	172.3	246.6	232.7	137.9	160.3
Final weight (lbs.)	179.2	169.9	231	223.7	177.4	241.1	217.2	135.1	160.8
Difference (lbs.)	-5.8	-7.6	-3.6	6.7	5.1	-5.5	-15.5	-2.8	0.5
% change	-3.1	-4.3	-1.5	3.1	3.0	-2.2	-6.7	-2.0	0.3
Initial Abdominal Girth (in.)	48	39.5	45.5	44	39.5	45.5	56.5	39	48
Final Abdominal Girth (in.)	47.5	39	44	46	39.5	43	54	40	47
Difference (in.)	-0.5	-0.5	-1.5	2	0	-2.5	-2.5	1	-1
% change	-1.0	-1.3	-3.3	4.5	0	-5.5	-4.4	2.6	-2.1
Initial Body Fat (%)	49.7	33	24.1	16.5	36.2	34.6	-	28.9	43.3
Final Body Fat (%)	47.5	31.8	23.2	18.4	35.9	36.8	-	26.8	43.1
Difference (%)	-2.2	-1.2	-0.9	1.9	-0.3	2.2	-	-2.1	-0.2
% change	-4.4	-3.6	-3.7	11.5	-0.8	6.4	-	-7.3	-0.5

APPENDIX J

WEIGHT DATA FROM LOSEIT

Table 37: Weights recorded in LoseIt!

Subject	1	2	3	4	5	6	7	8	9
Initial Weight	185	177.5	234.6	217	172.3	246.6	232.7	137.9	160.3
15-Nov			228.0						
16-Nov			228.0	215.0					
17-Nov	164.3	176.3				249.0			
18-Nov									
19-Nov	168.5								
20-Nov	161.2					234.0			
21-Nov	167.8					234.0			
22-Nov	162.9					234.0	202.5	138.0	151.5
23-Nov									
24-Nov	155.3								
25-Nov	160.5								
26-Nov	162.8								
27-Nov	159.2								
28-Nov	162.6		217.0						
29-Nov	158.2		218.0			233.0	228.7		
30-Nov				207.7					
1-Dec	161.9					233.0	228.7		
2-Dec	160.3					233.0			
3-Dec	159.1					233.0			
4-Dec	158.8		218.0			233.0			
5-Dec	162.5								
6-Dec	158.1		217.0			244.0			149.5
7-Dec	159.3	144.8	218.0			233.0			
8-Dec	160.3			197.3					
9-Dec	150.0					233.0			149.5
10-Dec	150.8		224.0						
11-Dec	156.4	144.8	234.0	196.7					146.5
12-Dec	159.2		245.0			233.0			
13-Dec	159.3		226.0	190.7					
14-Dec	157.9		222.0	185.7					146.7
15-Dec	156.6			206.0		233.0			
16-Dec				190.0		233.0			
17-Dec	159.1			194.6					144.0
18-Dec	155.8		230.0	182.8					
19-Dec		164.9	222.0	196.3	178.6				
20-Dec				193.7					
21-Dec	179.1	164.9	229.0	216.7		240.0			
22-Dec	178.0		235.0	191.5		239.0			148.0

Table 37 (continued)

23-Dec	178.8	170.5							
24-Dec	175.9			184.9		239.0			
25-Dec	180.1		223.0						
26-Dec	184.1								
27-Dec	177.0		191.0	188.0					
28-Dec				187.6					
29-Dec	169.8		192.0			239.0			
30-Dec	174.9	170.5	189.0	187.6					
31-Dec	174.1			192.4					
1-Jan	173.1			184.9					
2-Jan	173.8		196.0						
3-Jan			200.0	186.0	134.0	239.0			
4-Jan			192.0		31.7				
5-Jan	173.8		192.0	181.0			228.7		
6-Jan					58.0				
7-Jan									
8-Jan	170.3								
9-Jan									
10-Jan				178.5					
11-Jan	173.8	161.4					227.4		
12-Jan	166.2	160.9			58.0	239.0			
13-Jan	170.6								
14-Jan	170.5	165.0							
15-Jan	172.1	158.3		205.8					
16-Jan	168.3					241.0			
17-Jan	174.3				181.2				
18-Jan				178.5	178.1	239.0			
19-Jan	174.3				178.1				
20-Jan									
21-Jan					9.1				
22-Jan				185.2					
23-Jan		152.7							
24-Jan				178.5	182.0				
25-Jan	173.1								
26-Jan									
27-Jan						235.0			
28-Jan									
29-Jan				205.0					
30-Jan									
31-Jan									
1-Feb									
2-Feb				188.6					
3-Feb									
4-Feb									
5-Feb									
6-Feb									
7-Feb									
8-Feb									
9-Feb									
Final	**179.2**	**169.9**	**231**	**223.7**	**177.4**	**241.1**	**217.2**	**135.1**	**160.8**

APPENDIX K

FINAL QUESTIONNAIRE ANSWERS

Table 38: Results from final questionnaire

Subject	1	2	3	4	5	6	7	8	9
1. Rating of Education Materials Satisfaction*	5	6	5	7	1	7	6	5	5
1a. Rating of Education Materials Helpfulness**	5	6	5	7	6	7	6	5	5
2. Rating of Online Meetings Satisfaction*	6	7	5	7	1	7	5	7	6
2a. Rating of Online Meetings Helpfulness**	6	7	5	6	6	7	6	7	7
3. Rating of LoseIt! Journal Satisfaction*	6	6	6	7	1	7	7	2	6
3a. Rating of LoseIt! Journal Helpfulness**	6	6	6	7	6	7	7	2	7
4. Rating of E-scale Satisfaction*	5	4	3	2	1	7	2	1	4
4a. Rating of E-scale Helpfulness**	5	4	2	2	6	3	2	1	3
5. Satisfaction with the overall program*	6	6	5	5	1	7	6	7	5
6. Likelihood of recommending the program to other wheelchair users	5	6	6	6	7	7	6	7	6
7. How many of the weekly lessons did you read fully?	All	9-11	6--8	All	All	All	All	1-2	9-11
8. The E-scale was easy to use****	6	6	4	6	7	7	2	7	7
9. The E-scale user interface (Tablet) met my expectations******	6	4	2	6	7	7	2	1	3
10. The E-scale reported my weight accurately******	5	2	2	1	1	1	1	1	3
11. Once the E-Scale becomes more accurate and reliable, I would prefer to use the E-scale instead of other weight measuring devices I have previously used******	7	6	6	6	7	7	6	1	6

Table 38 (continued)

Please list other weight monitoring devices you have used. 1=Roll-on scale 2=Wheelchair scale 3=Chair scale 4=Bathroom scale 5=Regular scale	-	5	1		-	4	2	2,3	-
Once the E-Scale is updated so that it is reliable and accurate, I would use it to monitor my weight in my home****	7	6	5	7	7	7	5	6	6
What, if any, issues did you have with using the E-scale? (choose all that apply) 1=Not Accurate 2=Tablet frequently did not work	2	1,2	1,2	1	1	1,2	1,2	1,2	1
Please indicate how likely it is that you would purchase the E-scale (fully functional and accurate) if it costs $200***	6	6	5	7	1	7	1	7	6
Please indicate how likely it is that you would purchase the E-scale (fully functional and accurate) if it costs $400***	5	4	2	4	0	4	1	1	4
Please indicate how likely it is that you would purchase the E-scale (fully functional and accurate) if it costs $600***	5	2	1	3	0	1	1	1	2

* 1=Extremely Dissatisfied, 7=Extremely Satisfied
** 1=Extremely Unhelpful, 7=Extremely Helpful
*** 1=Extremely Unlikely, 7=Extremely Likely
**** 1=Completely Disagree, 7=Completely Agree

SYSTEM USABILITY SCALE SCORES*

Table 39: System Usability Scale scores

Subject	1	2	3	4	5	6	7	8	9
1. I think that I would like to use this system frequently	4	3	3	0	2	4	2	1	3
2. I found the system unnecessarily complex	3	3	2	4	4	4	3	4	4
3. I thought the system was easy to use	3	4	2	3	4	4	1	4	4
4. I think that I would need the support of a technical person to be able to use this system	1	3	3	4	4	3	0	3	4
5. I found the various functions in this system were well integrated	2	3	1	2	4	4	2	4	3
6. I thought there was too much inconsistency in this system	0	1	0	0	0	2	0	0	0
7. I would imagine that most people would learn to use this system very quickly	3	4	3	4	4	4	2	4	3
8. I found the system very cumbersome to use	3	3	3	3	4	4	2	0	4
9. I felt very confident using the system	3	4	2	0	4	4	0	4	3
10. I needed to learn a lot of things before I could get going with this system	3	4	3	4	4	4	3	4	4

***** These are the scores after the subjects' answers were converted to 0-4 as described in Appendix G

APPENDIX L

E-SCALE PLOTS FROM WEIGHT LOSS STUDY

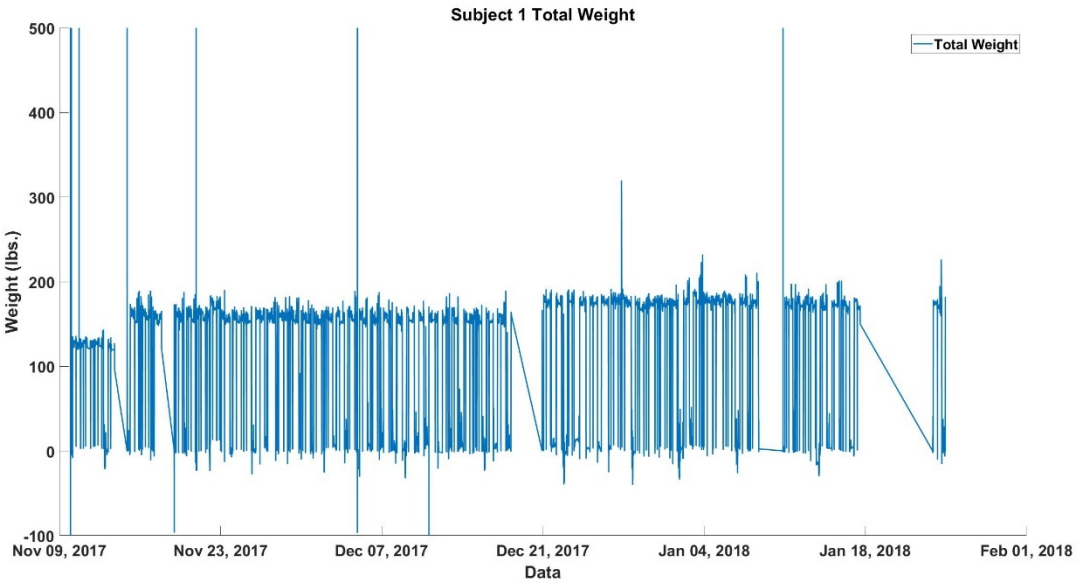


Figure 39: Subject 1 total weight

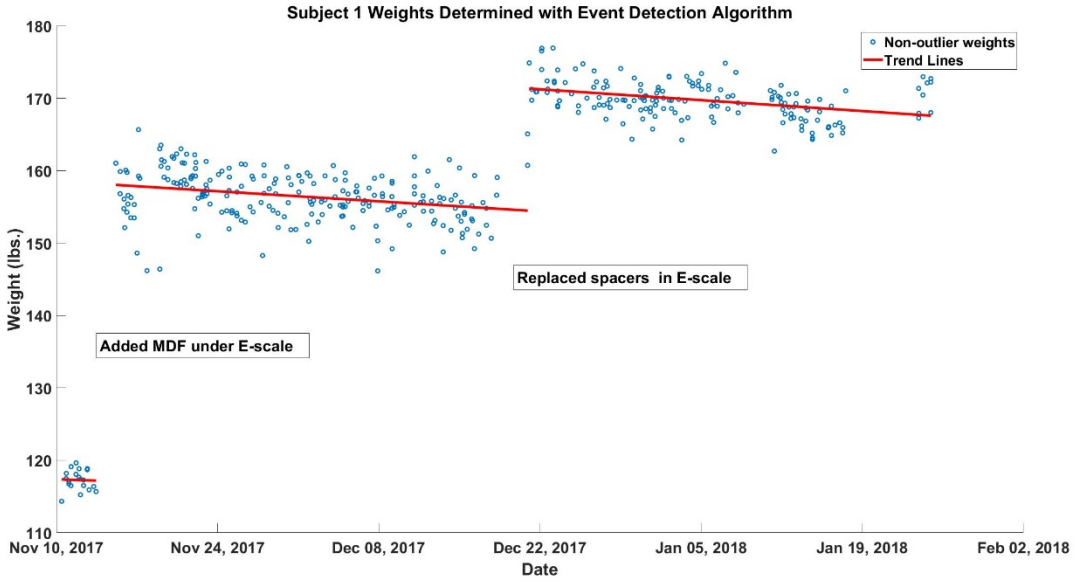


Figure 40: Subject 1 plot of weights

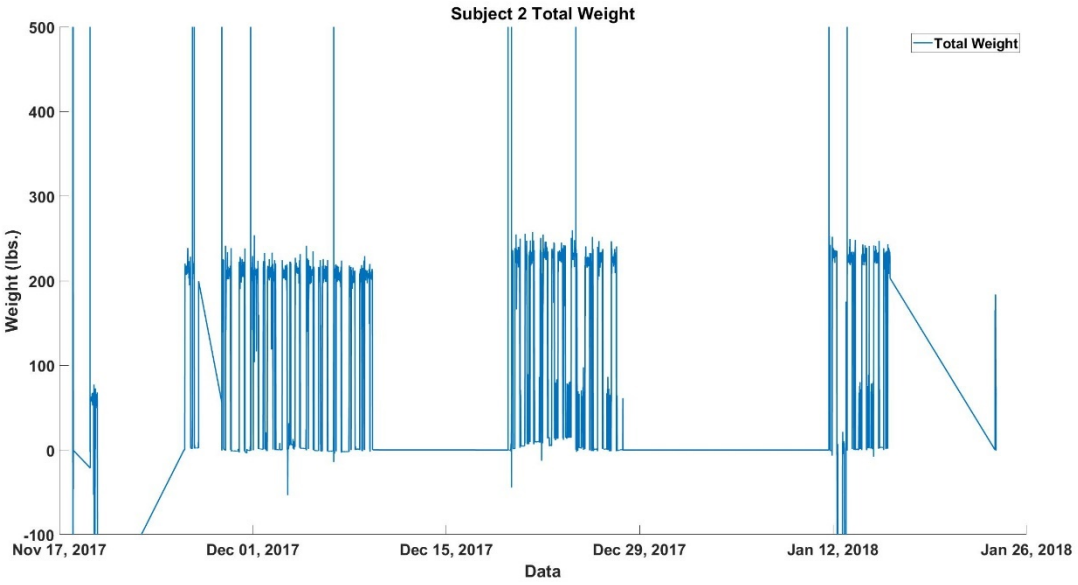


Figure 41: Subject 2 total weight

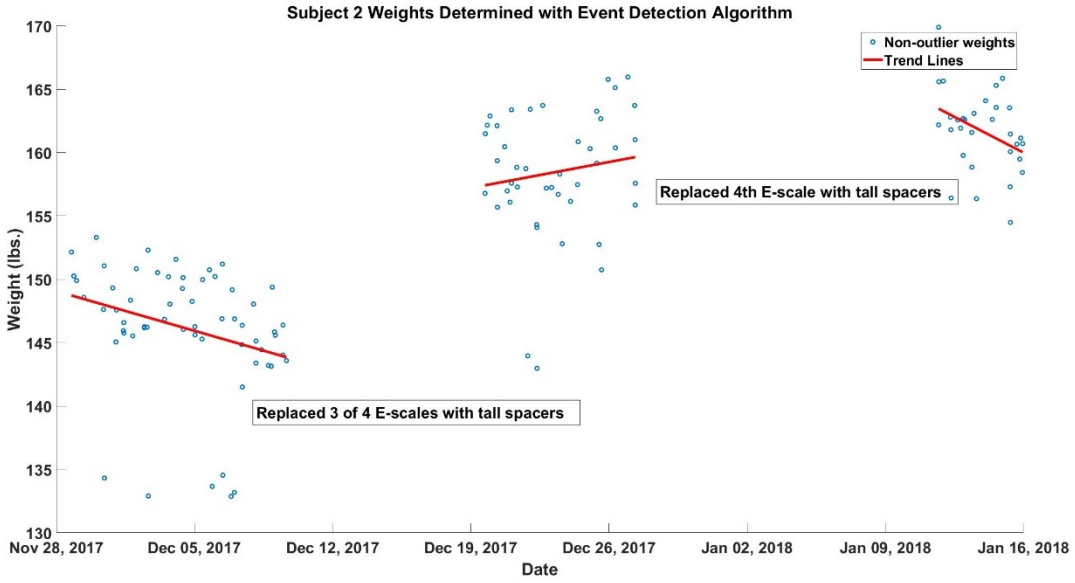


Figure 42: Subject 2 plot of weights

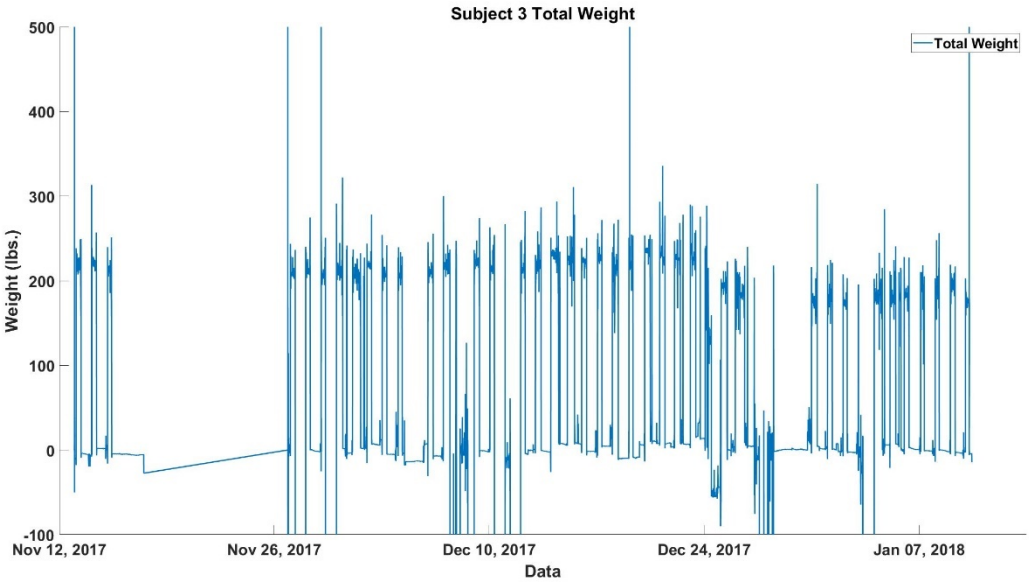


Figure 43: Subject 3 total weight

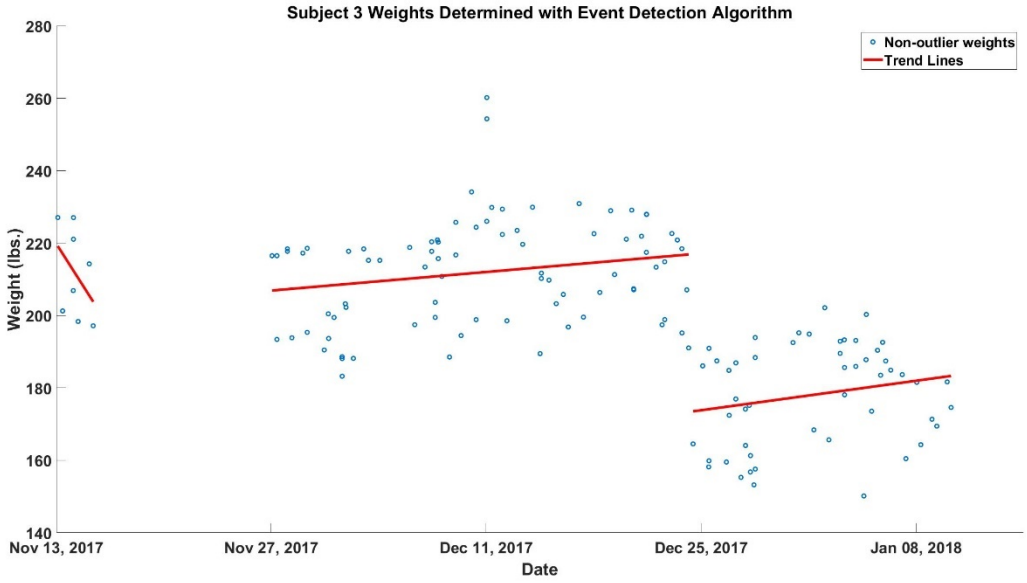


Figure 44: Subject 3 plot of weights

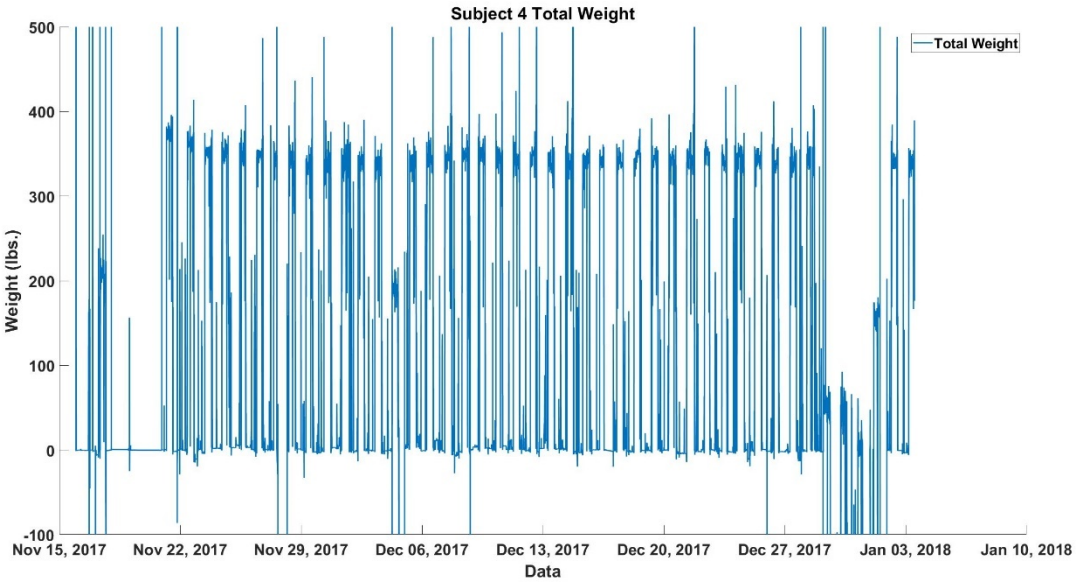


Figure 45: Subject 4 total weight

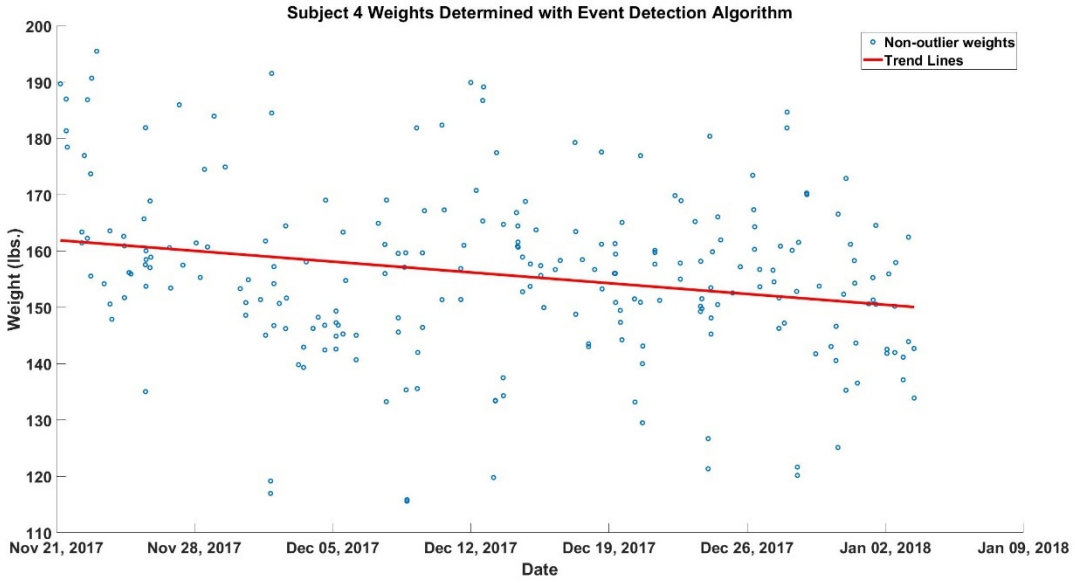


Figure 46: Subject 4 plot of weights

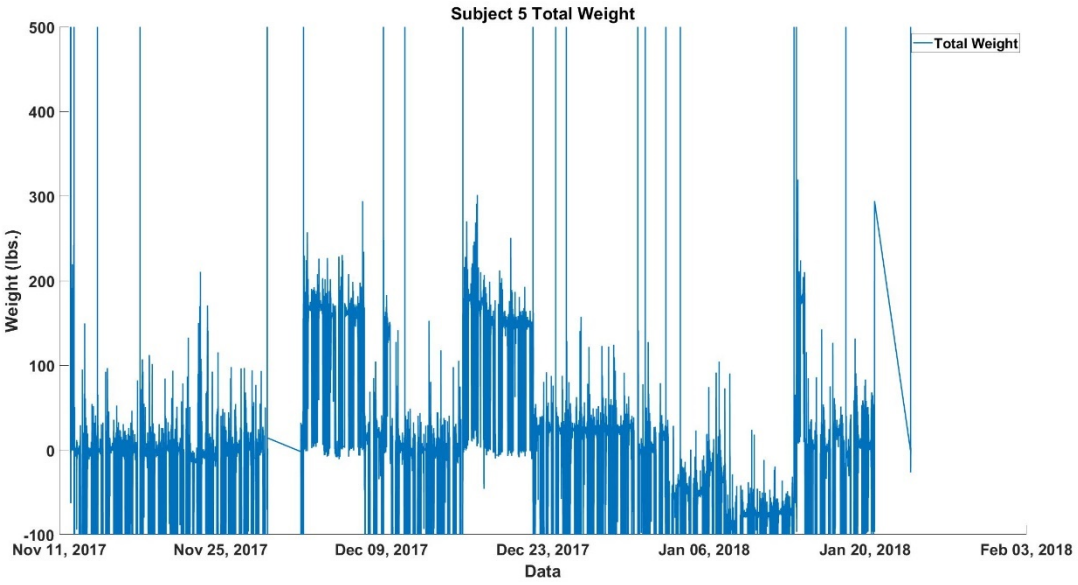


Figure 47: Subject 5 total weight

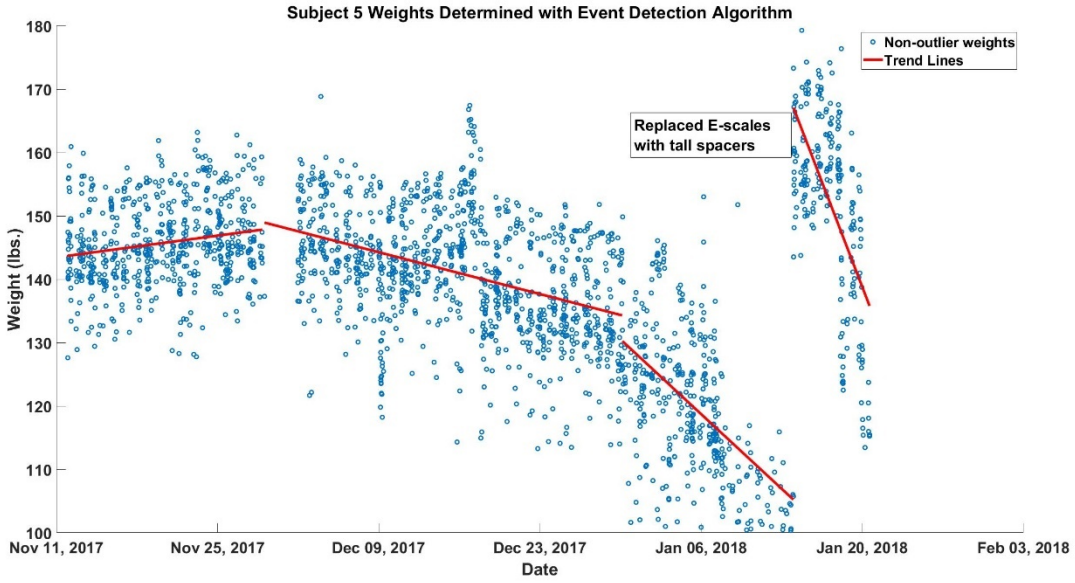


Figure 48: Subject 5 plot of weights

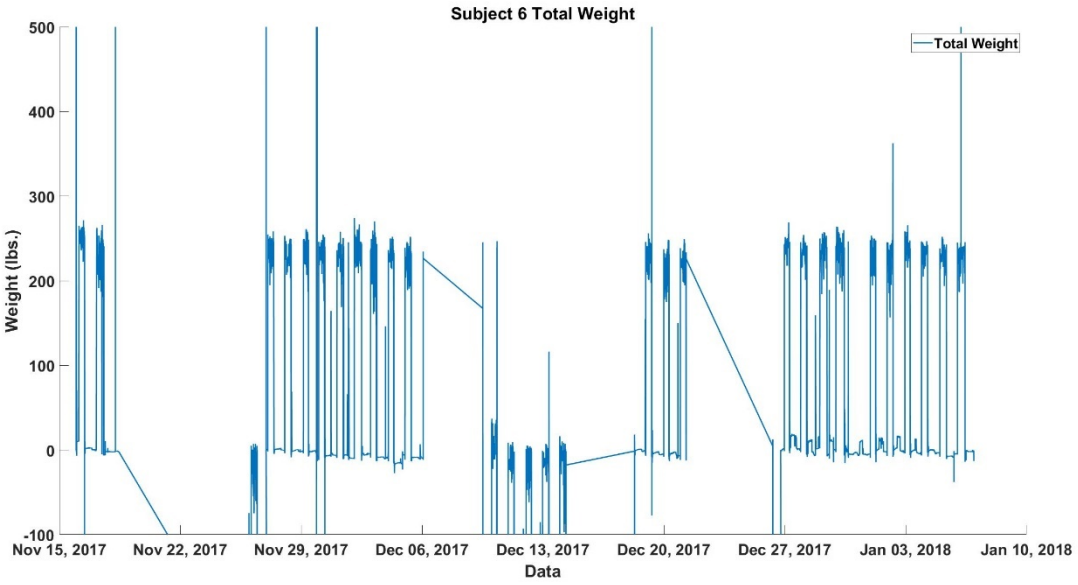


Figure 49: Subject 6 total weight

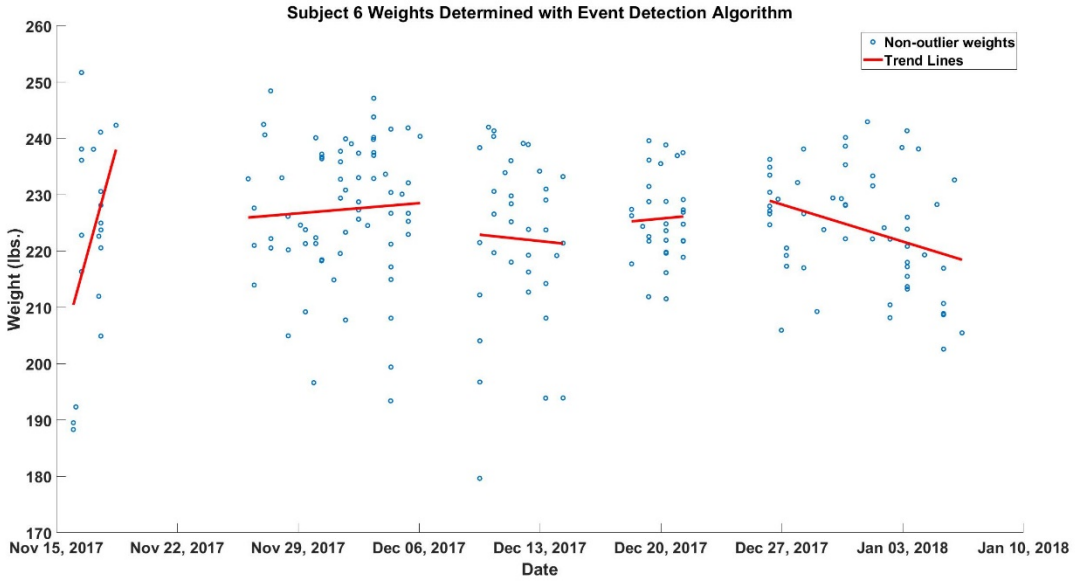


Figure 50: Subject 6 plot of weights

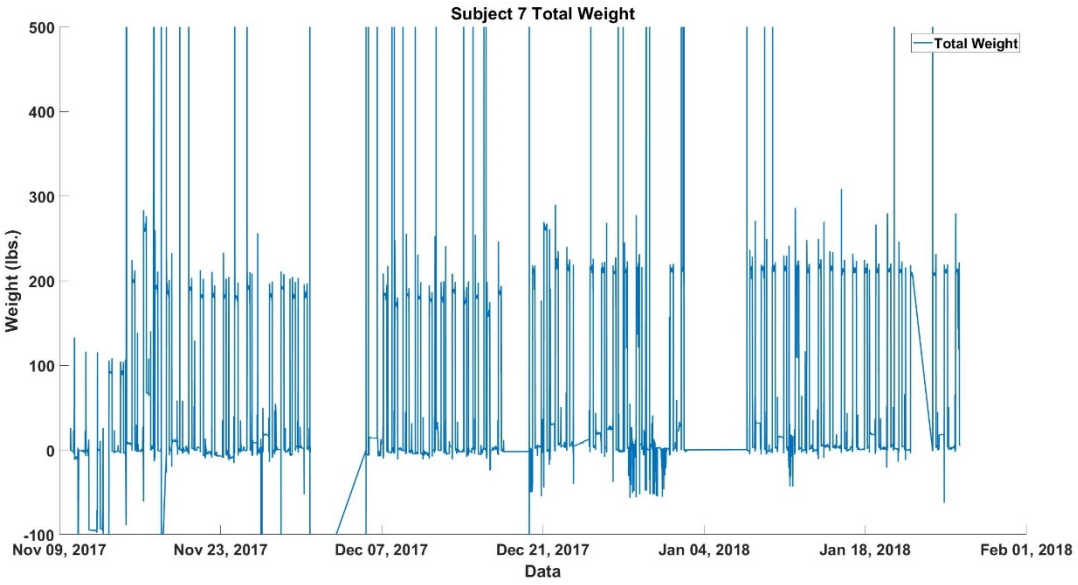


Figure 51: Subject 7 total weight

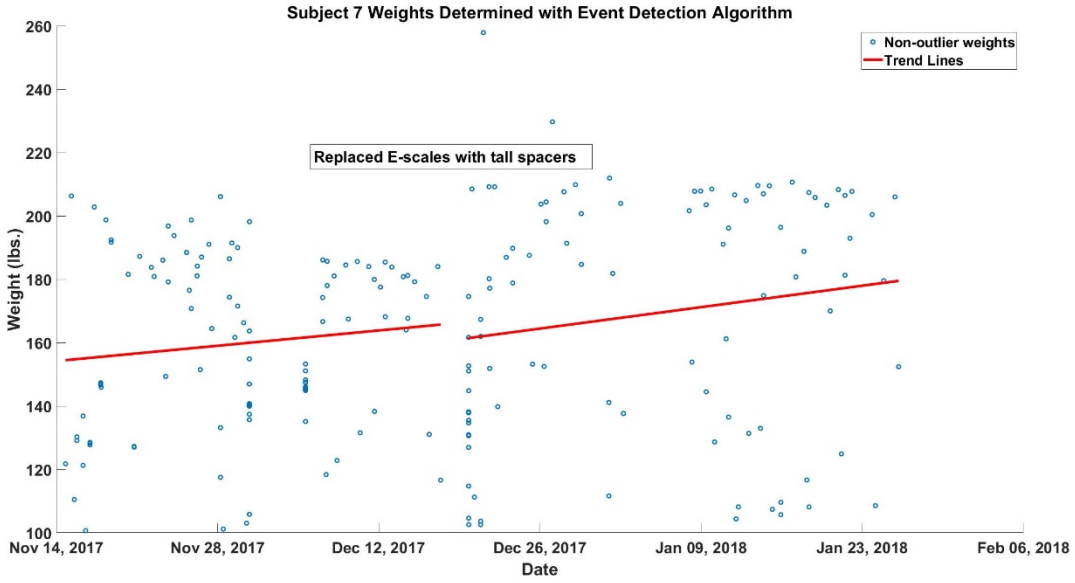


Figure 52: Subject 7 plot of weights

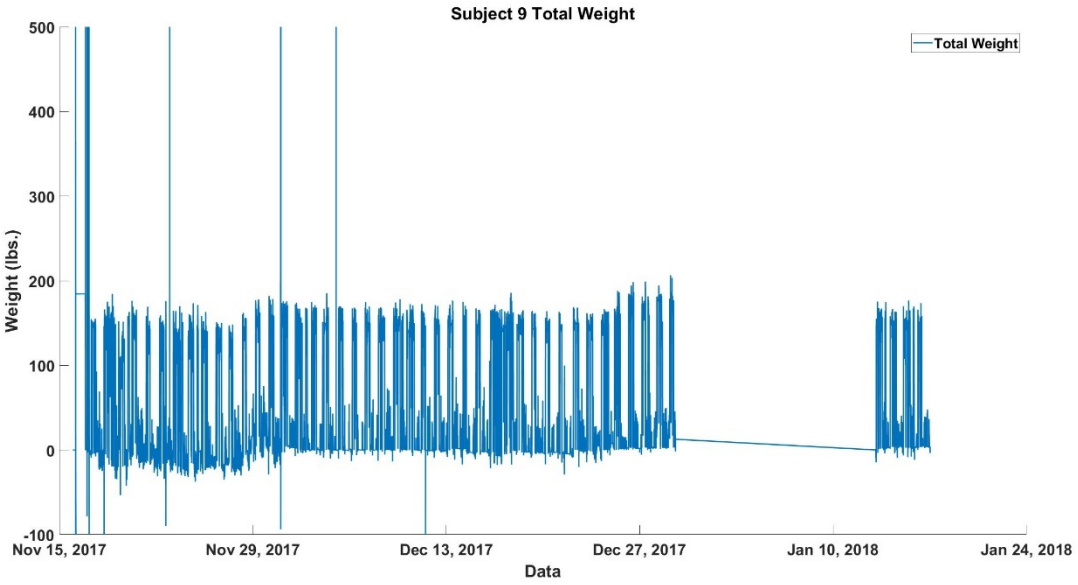


Figure 53: Subject 9 total weight

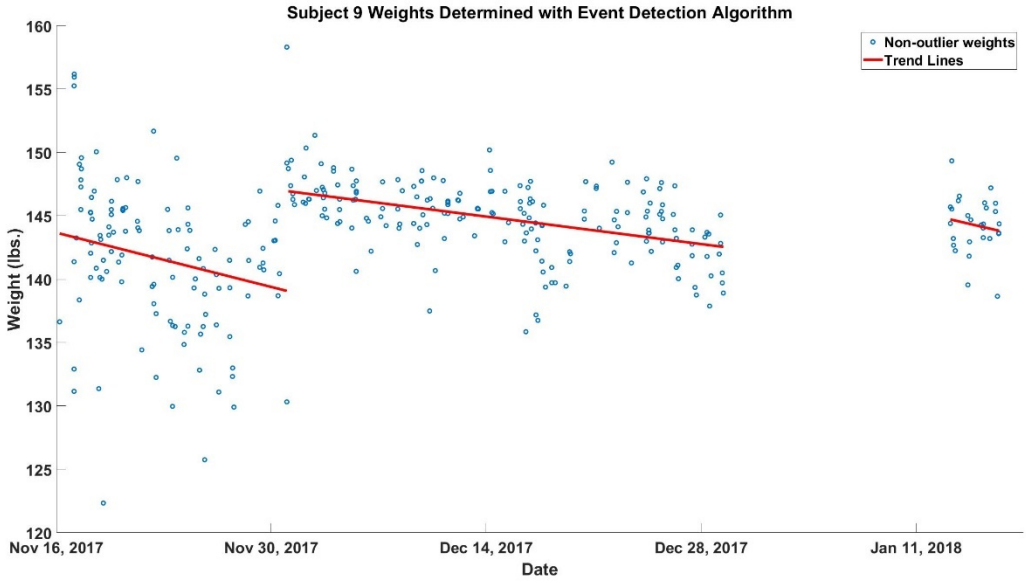


Figure 54: Subject 9 plot of weights

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