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Development and Evaluation of Pneumatic Powered Mobility Devices

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Development and Evaluation of Pneumatic Powered Mobility

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University of Pittsburgh, 2020

The performance of battery-powered mobility devices (PMDs) has continually improved since their invention in the 1950s due to advances in electronics and their control systems. Yet they continue to experience increases in repairs and utilize battery technologies that require long recharge times and frequent, expensive replacement. Although advances in battery technologies are ongoing, the technology is expensive and raises safety concerns. The need for the development of alternative power sources has been voiced by consumers as well as providers of PMDs. Alternative forms of power need to be researched to further improve the performance of powered mobility devices. The purpose of this project was to develop a novel power system for powered mobility devices driven by compressed air and evaluate its performance in a real-world setting. This was accomplished by following the product development process with the addition of participatory action design to maximize the potential for meeting end user's needs. Through the development of several iterations of mobility scooter prototypes, a pneumatic-powered system was created and optimized for efficiency. The results of the mobility scooter developments were later incorporated into the design of a powered wheelchair configuration. The two types of mobility devices were tested using ISO Wheelchair Standards to evaluate their safety, durability and maneuverability of which both devices performed comparatively to their battery-powered equivalents. Additionally, a pneumatic-powered shopping cart configuration was created to test its usage in a grocery store setting. K-Means clustering analysis was performed to evaluate whether certain demographics of individuals preferred to use the pneumatic-powered cart versus the battery-powered cart of which the results revealed individuals younger than 54 years old and those who do not own a mobility device preferred to use the pneumatic-powered shopping cart over the battery-powered shopping cart. Overall, the feasibility for pneumatic-powered mobility devices to serve as an alternative to battery-powered mobility devices is plausible. Although, further improvements as well as additional pilot tests are needed prior to commercialization.

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Preface

I would like to thank everyone at the Human Engineering Research Laboratories (HERL) for their support and assistance over the past 5+ years. I would especially like to acknowledge my advisor and committee chair, Dr. Rory Cooper for his guidance and mentorship, it has been an honor being one of your students as well as sharing birthdays! Thank you to my other committee members: Dr. Susan Cohen, Dr. Mark Schmeler, Dr. Urs Schneider and Dr. Hongwu Wang for your time reviewing my work. Also, I would like to recognize the HERL machine shop staff, especially Ben Gebrosky for your patience throughout the project and for not killing me for my numerous screw ups! Thank you to everyone at the Innovation Institute and Big Idea Center for your guidance and knowledge of how to be a successful entrepreneur. Thank you to Dr. Mary Goldberg for introducing me to HERL and encouraging me to apply. Additional thanks to my nurse, Kathy and the dozens of personal care assistants for your help getting me through the day. Most importantly, thank you to my family for always providing the love, support and encouragement. Love you all!

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1.0 Introduction

1.1 Study Purpose

In 2017, there were an estimated 42.8 million people with disabilities in the United States (US), comprising of 13.2% of the US population, an increase from 12.7% in 2008 [1]. According to the 2018 American Community Survey, 6.8% (20.6 million) of the US population had an ambulatory disability with 21.4% (4.41 million) being ages 65 and over [2]. A 2014 publication on Americans with disabilities by the US Census Bureau reported 5.5 million people used a wheelchair [3], up from 3.6 million reported in 2010 [4]. Over the next several years, the population of individuals turning 65 or older is predicted to grow at an annualized rate of 3.2% and reach 61.6 million people in 2023 [5], yet the total US population is forecasted to grow at a significantly slower rate which indicates those ages 65 and over will contribute an increasingly significant portion of the population towards the usage of mobility devices.

Powered Mobility Devices (PMDs) have been portrayed as the most enabling technology prescribed for a person with a disability [6]. Their use has been shown to improve community integration, function, independence, participation [6-9], comfort [10, 11] and quality of life [10, 12]. However, PMDs can both help and hinder community participation; when they function well, PMDs can offer access and autonomy, but maintenance needs or malfunctions may sometimes interfere with participating in the community [13]. Repairs to the electrical, power and control systems of battery PMDs are the most common [14] and their frequency has been increasing every year [15]. One study found that 65% of the 591 survey participants required at least one repair every 6 months with half of them experiencing adverse consequences including being stranded, or missing medical appointments, work or school [14]. Unfortunately, devices that require frequent repairs or maintenance may result in device abandonment, or higher rate of injury [14] and accidents requiring hospitalization [16-18] and sometimes even death [18].

For years, major advancements in motors, electronics and control systems have improved the usability and drivability of PMDs [19-22]. However, the adoption of newer battery technologies has not occurred due to safety, cost and reliability concerns. Although gel-cell lead-acid batteries are the industry standard, they pose safety concerns including risks of fire, outgassing, electromagnetic interference and electrical shock. Numerous wrongful deaths have occurred as a result of mobility devices catching fire [23-26]. In 2000, wheelchair manufacturer Invacare and other manufacturers including Pride Mobility Products Corp. were named in wrongful death lawsuits due to wheelchair fires [23, 27].

These problems demonstrate a clear need for the investigation and development of new power sources for PMDs. This need has been justified in a national survey of over 1000 individuals, including 500 veterans with disabilities who listed new power sources as the “most important” or “important” technology needing developed in the category of mobility/transportation inventions [28]. Another national survey reported 72% of battery PMD users and 75% of clinicians who provide battery PMDs, ranked new power sources for mobility devices as an “important” or the “most important” futuristic mobility invention [29]. Many professional organizations have also advocated for this development including the Institute of Medicine, the Rehabilitation Engineering Research Center on Technology Transfer and the Center for Compact and Efficient Fluid Power [30-32]. To summarize, future increases in the use of PMDs, repairs and safety issues with current PMD technologies and demand for new power sources by end-users and clinicians each justify the need for the development of a novel power system for mobility devices that has the capability to address these issues and demands.

1.2 Preliminary Research

1.2.1 Battery-Powered Mobility devices

The electric wheelchair was invented at the National Research Council of Canada in 1953 by George Klein to provide mobility for World War II veterans [33]. Klein’s prototype was essentially a standard, manual wheelchair with a motor attached, propelled by batteries and controlled by the user through a joystick (Figure 1) [34]. Although wheelchair technologies are continually evolving, George Klein’s electric wheelchair concept paved the way. Since Klein’s invention, batteries used in PMDs have progressed from wet-cell lead-acid batteries to today’s most commonly used gel-cell lead-acid batteries due to their low maintenance and airline travel safety [35, 36]. The gel-cell battery continues to remain the battery of choice for PMDs because it meets many of the needs of most PMD users, yet their low energy density, short lifecycle, heavy weight and long recharge times are problematic.

Figure 1: George Klein's Prototype Electric Wheelchair

Over the course of the expected 5-year lifetime of a PMD, batteries need to be replaced approximately 3-5 times at a cost ranging between \$200-\$800 per occasion, totaling between \$600-\$4000 [37]. Although, battery lifetime varies based on numerous factors including travel distance, terrain type, frequency of use, charging habits and weight [38]. After replacement, it is essential that the discarded batteries be disposed of correctly to prevent harm to the environment. Lead-acid battery recycling is a major source of environmental contamination and human exposure because it is carried out without the necessary processes and technologies [39]. Without adequate standards and enforcement of regulatory controls, industrial scale recycling facilities can cause substantial environmental contamination [40].

1.2.2 Alternative Power Sources

Battery chemistries such as nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), or lithium-ion (Li-Ion) serve as the simplest alternatives for PMDs because they are nearly drop-in replacements. NiCd batteries are robust, capable of deep discharging, and offer longer lifecycles than NiMH and Li-Ion, yet are toxic to the environment and susceptible to the memory effect which shortens their lifespan and decreases charging capacity [41, 42]. NiCd and NiMH have similar charging/discharging characteristics, but NiMH offers twice the capacity at approximately the same size and weight [41]. Li-Ion batteries have the lowest weight and highest capacity of the three battery chemistries. Unlike NiCd and NiMH, Li-Ion batteries aren't impacted by the battery memory effect and are non-toxic to the environment. A disadvantage of Li-Ion is the need for an integrated circuit that monitors the input and output current and voltage. Without the circuit, the battery could potentially have a thermal runaway resulting in the battery catching fire [41]. In terms of cost, Li-Ion is the most expensive, followed by NiMH, lead-acid, then NiCd [43]. Lastly, all three battery chemistries have substantially shorter recharge times compared to lead-acid batteries. Table 1 provides a summary comparison of each battery chemistry in terms of specific energy, lifecycles, battery memory, toxicity, charge time and cost; of which lead-acid batteries are outperformed in all categories except for cost [44].

Table 1: Battery Chemistry Comparison

	Lead-acid	**NiCd**	**NiMH**	**Li-Ion**
Specific energy (Wh/kg)	30-50	45-80	60-120	90-190
Lifecycles	200-300	1000	300-500	300-700
Battery memory	No	Yes	Yes	No
Toxicity	Very high	Very high	Low	Low
Charge time	6-8 hours	1-2 hours	2-4 hours	2-4 hours
Cost	Low	Moderate	Moderate	High

In addition to different battery chemistries, another potential electric power source is a fuel-cell which produces electricity using an electrochemical process that converts hydrogen and oxygen into water. For polymer exchange membrane fuel cell (PEMFC) systems, 70% of their costs include the metal catalysts (typically platinum), gas diffusion layers, proton exchange membranes, and bipolar plates [45]. PEMFC systems are believed to be the most likely candidate used for transportation due to their high-power density and relatively low operating temperatures [46]. Despite fuel cells being non-toxic and greenhouse gas emissions free, hydrogen itself is flammable and explosive [47]. Furthermore, fuel cells require a constant replenishment of pure hydrogen to continue working, thus the design of safe, reliable hydrogen storage systems is crucial when considering their implementation in PMDs. Although hydrogen is the most common element in the universe, it rarely exists naturally on earth in its elemental form [48]. Thus, it must be extracted from compounds such as fossil fuels or water [49] which requires energy [45] and is expensive [50]. Several powered wheelchair prototypes have been developed incorporating fuel-cell technology into their design. One study developed a hybrid fuel-cell power system that reduced the charging frequency by 98% when compared to a traditional fuel-cell set up [51]. Several other prototypes suggested that fuel cells can act as range extenders when used alongside batteries [52, 53].

Other potential alternatives that could provide electrical energy are solar power and supercapacitors. Photovoltaic panels or solar panels convert light from the sun into direct current energy that could be used to recharge PMD batteries. One research team developed a proof of concept prototype that could travel uninterrupted for 8 km or up to four hours continuously. Other findings from the same research included: minimized recharging times by increasing the capacity of the solar panels, the solar panels were sensitive to vibrations and flat surfaces were preferred over steep ones [54]. Another solar powered wheelchair prototype increased its travel range by 26% compared to being powered by the battery alone [55]. As for supercapacitors, they are best implemented during instances when rapid charge and discharge cycles are preferred rather than the long-term storage required for PMDs [56]. As a result, they would need to be combined with another power source to be suitable [57].

For each of the previous power sources, electrical energy was stored or produced and used to drive an electric motor. For power sources such as compressed gas or combustible gases/liquids, their stored energy provides rotational movement to the wheels either directly through a motor or via a transmission/gearbox. Potential compressed gases include air, nitrogen or carbon dioxide (CO2). High-pressure air (HPA) tanks can be filled with either compressed air (commonly over 70% nitrogen) or pure nitrogen, although compressed air is more common because it is more readily available. Some HPA tanks wrapped in carbon fiber can hold pressures up to 310 bar [58] which allows them to be lighter weight compared to aluminum and steel, but at the expense of increased cost. Although HPA tanks are more expensive than CO2 tanks, compressed air and nitrogen are more stable and reliable when operating at different temperatures. A major disadvantage of CO2 is its inefficiency changing from a liquid to a gas because CO2 tanks are filled with liquid CO2. Overall, compressed gases are advantageous due to their tank life expectancy (up to 15 years), robustness in wet environments, environmental friendliness, quick refill capability (2-3 minutes), lighter weight and lower operating costs.

As for combustible gases or liquids such as liquid propane, natural gas or methane; there is concern regarding their emissions when used inside a home or building. The World Health Organization recommends that carbon monoxide (CO) have emission rates lower than 0.16 g/min when unvented and 0.59 g/min when vented [59]. One study reported that natural gas stoves contribute to about 30% and 21% of the indoor CO concentration in the summer and winter, respectively. They predicted that homes that did not use venting range hoods exceeded CO concentration guidelines [60]. In the event combustible gases/liquids are utilized in PMD, the devices emissions must carefully be monitored to ensure the users aren’t exposed to harmful levels of CO and other gases.

Lastly, a hybrid system could be developed by combining multiple energy sources into a single system based on their pros and cons (Table 2), rather than having a single source of energy on board a PMD. For example, one energy source could be chosen for long distance travel or when outdoors (i.e. batteries or combustible gases/fluids) while another energy source could be chosen for traveling short distances (i.e. compressed gas or fuel cells). One research team developed a hybrid power wheelchair using a battery, photovoltaic solar cell and a hydrogen fuel cell whose energy control system determined the optimal source of energy to be used based on the device's operating conditions [61]. Although, concerns of a hybrid system are increased cost, maintenance and weight deem them unlikely for commercialization.

Table 2: Power Source Comparison

Power Source	Pros	Cons
Lead-acid	• Reliable • Low self-discharge	• Toxic • Recharge time • Heavyweight
NiCd	• Quick recharge • # Lifecycles	• Toxic • Heavyweight • Memory effect
NiMH	• Non-toxic • Quick recharge • High capacity	• Self-discharge • Memory effect • Expensive • Special charger
Li-Ion	• Non-toxic • Quick recharge • Lightweight • High capacity	• Fire/explosion risk • Expensive • Monitoring circuit
Supercapacitors	• #Lifecycles • Quick recharge • Energy density	• Heavyweight • Expensive
Fuel cells	• Non-toxic • Efficiency • No recharging	• Expensive • Constant fuel source • Infrastructure
Compressed gas	• Quick recharge • Lightweight • Waterproof • # Lifecycles	• Infrastructure • Efficiency • Energy density
Combustible gases/liquids	• Reliable • Waterproof • # Lifecycles	• Emissions • Fire/explosion risk • Heavyweight

1.2.3 Alternative Power Source Selection

The determination of which alternative power source to pursue for the development of a prototype was evaluated using a selection matrix, a tool for ranking concepts based on a list of selection criteria [62]. Using lead-acid as the reference power source (rated as 0), each power source was rated as + for “better than,” 0 for “same as,” or - for “worse than”. Explanations for each selection criterion rating are below:

- Charge time: (+) for shorter charge time, (0) for the same charge time and (-) for longer charge time
- Memory/discharge: (+) if battery memory and discharge does not occur, (0) if battery memory or discharge occurs and (-) if both battery memory and discharge does occur
- Weight: (+) if lighter weight, (0) if same weight and (-) if heavier weight
- Lifecycles: (+) if higher number of lifecycles, (0) if same number of lifecycles and (-) if lower number of lifecycles
- Toxicity: (+) if non-toxic and (0) if toxic
- Safety: (+) if safer, (0) if as safe and (-) more unsafe
- Cost: (+) if less expensive, (0) if similar cost and (-) if more expensive

The rating of each power source was based on the results of the review of alternative power sources. The following selection matrix was used to determine which power source to develop a prototype (Table 3). As a result of compressed gas being the dominant power source, a concept scoring matrix was not created. Of the compressed gas options, air was chosen as the gas of choice to create a prototype due to its availability, reliability and stability at different temperatures.

Table 3: Power Source Selection Matrix

	Power Sources					
Selection Criteria	**NiCd**	**NiMH**	**Li-Ion**	**Lead acid**	**Compressed gas**	**Combustible gases/liquids**
Charge time	+	+	+	0	+	+
Memory/discharge	-	-	0	0	+	+
Weight	+	+	+	0	+	0
Lifecycles	+	+	+	0	+	+
Toxicity	0	+	+	0	+	+
Safety	0	0	-	0	+	-
Cost	+	-	-	0	+	0
Sum +'s	4	4	4	0	7	4
Sum 0's	2	1	1	7	0	2
Sum -'s	1	2	2	0	0	1
Net Score	3	2	2	0	7	3
Rank	2	4	4	6	1	2

1.3 Research Aims

The overarching goal of this project was to develop and evaluate a pneumatic-powered system for PMDs. The process for accomplishing the study's goal followed the product development process and incorporated participatory action design involving end users, clinicians, industry experts and engineers. The successful development of a pneumatic-powered mobility device could introduce a safer, more reliable and user-friendly option that could improve user satisfaction and quality of life. The methods used to achieve the study's goal were driven by the following objectives:

- **Objective 1**: Create a proof of concept prototype to test the feasibility of compressed air as an energy source by replacing the electrical components of an existing mobility scooter with pneumatic components. If feasible, optimize the prototype for range efficiency.

- **Objective 2**: Design and manufacture a mobility scooter to integrate the pneumatic system. Perform ISO 7176 Wheelchair Standards testing to evaluate the prototype’s safety, durability and maneuverability.
- **Objective 3**: Develop a pneumatically powered wheelchair and perform ISO 7176 Wheelchair Standards testing.
- **Objective 4**: Conduct a pilot study to evaluate and obtain feedback from end users using the pneumatic-powered mobility device in a real-world setting.

2.0 Development of Pneumatic Technology for Powered Mobility Devices

2.1 Introduction

The concept of using compressed air as a means of transportation isn’t new. Air-powered vehicles have been in existence since the 1800s, with locomotives being the first. Several individuals claim to have invented the first air-powered car in the 1920s and 1930s, yet the inventor who developed the first air-powered car is unknown [63]. Indian carmaker, Tata, claimed that their Air Car was going into production in 2012 and be one of the cheapest, simplest cars on the road [64]. However, commercialization was delayed for fine tuning. Then in 2015, plans were made for Tata to work with Motor Development International (MDI) to commercialize MDI’s AirPod in Hawaii [65]. Although, the AirPod has not gone into production as of July 2016, which experts suggest is due to its limited range and lack of infrastructure to recharge the air tanks [64].

It’s probable PMD’s powered by compressed air won’t be impacted by the same issues, as previous research found that most PMD users travel indoors and short distances each day [66-68]. Furthermore, the increased reliability and lower maintenance costs of pneumatic PMDs could justify purchase of recharging stations and potentially could drive the industry towards replacing electric PMDs with pneumatic PMDs. The recharging stations would likely be in close proximity to users, similar to battery chargers currently. Moreover, locations that accommodate fleets of PMDs such as long-term care facilities, shopping plazas, grocery stores, hospitals and schools could practically accommodate recharging stations. Other advantages pneumatic systems offer over electric systems are their capability to be driven in wet environments such as beaches and water parks in addition to their decreased weight which allows for easier transportability.

The purpose of this research was to investigate whether pneumatic technology in PMDs is a feasible replacement for battery PMDs. Several prototypes were created, a proof of concept prototype served as a test bed to determine feasibility and the optimal configuration of parameters and components to achieve the greatest driving range, which led to the development of the 1st generation of the pneumatic-powered mobility scooter, the PneuScooter. ISO 7176 Wheelchair Standards of the 1st generation were performed in addition to further performance testing using different air tank configurations and gear ratios. Unfortunately, during standards testing, the 1st generation experienced a catastrophic frame failure requiring a redesign of the frame, leading to the creation of the 2nd generation PneuScooter. Lastly, the 2nd generation PneuScooter underwent standards testing and the results were compared with similar electric-powered mobility scooters. Figure 2 provides a breakdown of the overall process to develop the PneuScooter.

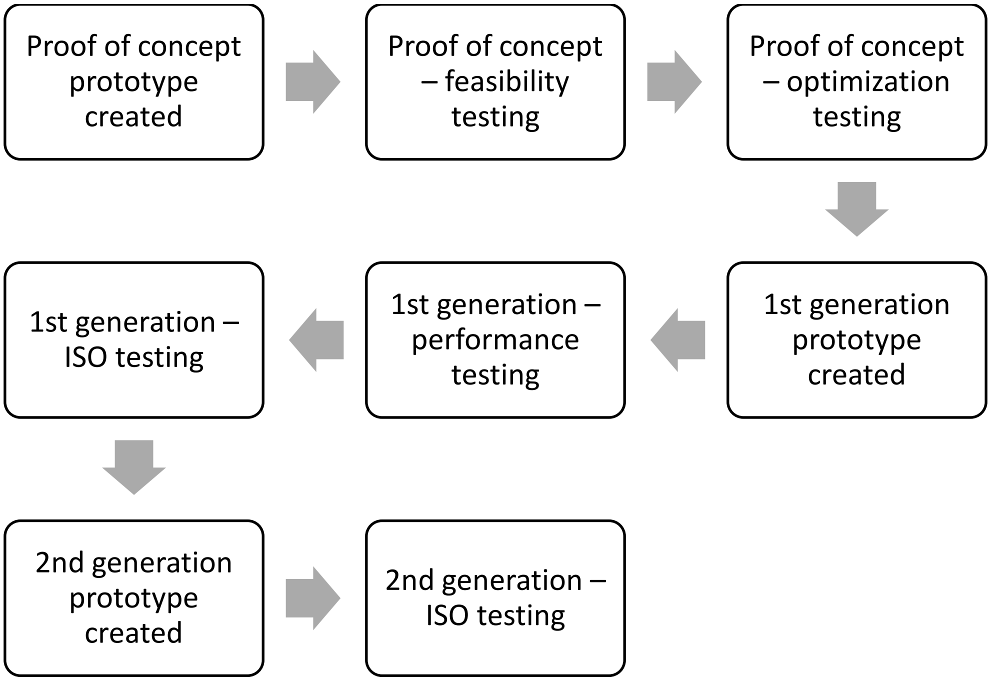


Figure 2: PneuScooter Development Process

2.2 Methods

2.2.1 Proof of Concept

The investigation into the feasibility of using compressed air in a mobility device began with the creation of a proof of concept prototype by modifying an existing electric-powered mobility scooter (Figure 3). The original electronic components including electric motor, computer, batteries and electrical wiring were removed and replaced with pneumatic components consisting of a directional control valve, flow control valve, airline tubing, regulator, air tank and pneumatic motor. The directional control valve made it possible for the scooter to be driven forward or backward while the flow control valve acted as a speed controller, restricting the airflow to the pneumatic motor.

Figure 3: Proof of Concept Prototype

The electric-powered mobility scooter frame was modified to mount the pneumatic motor and be configured as a 3-wheel reverse tadpole scooter or 4-wheel scooter. A reverse tadpole design has two front wheels and one rear wheel driven by the motor. The 4-wheel configuration replaced the original electric drive system with a limited slip differential that was connected to the pneumatic motor via a chain and sprocket. For the 3-wheel configuration, the wheel was directly mounted to the pneumatic motor output shaft and the differential, sprockets and chain were removed. Images of the modified electric-powered mobility scooter frame to accommodate the 4-wheel and 3-wheel configurations are shown in Figure 4.

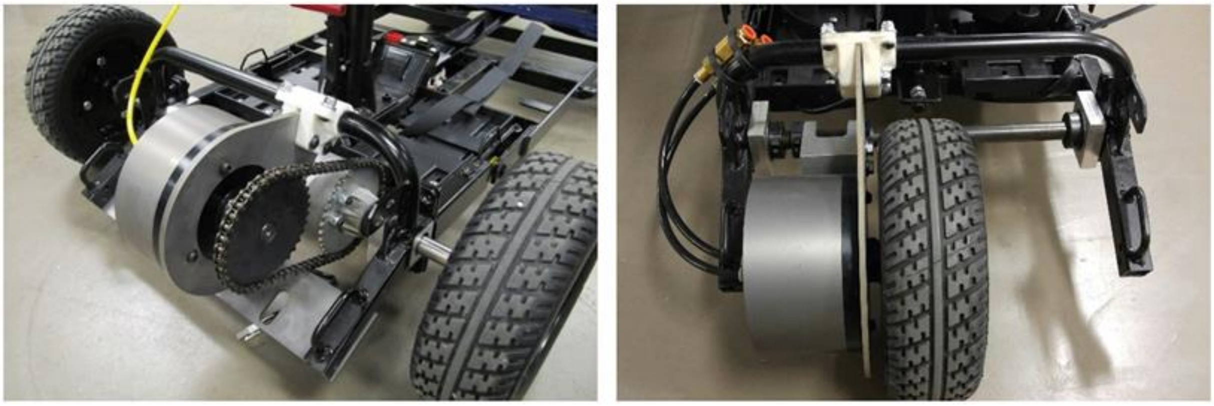


Figure 4: Proof of Concept Configurations: 4-wheel (left) and 3-wheel (right)

2.2.2 Feasibility and Optimization Testing

Feasibility testing was performed using the 4-wheel proof of concept prototype to determine whether the device could travel a practical distance on a viable amount of air. A practical distance was defined as traveling a minimum 500 m over a flat surface using a 1.44 L air tank pressurized to 310 bar. The test was performed using a PTM Mechatronics PMO 1800 radial piston motor [69], 6.35 mm diameter airline tubing, 6.21 bar operating pressure and a 1:1 gear ratio. The prototype was driven at 1.4 m/s over a flat surface until the air tank was empty and the prototype came to a stop.

After confirming feasibility, the proof of concept prototype was used to test different configurations of components and parameters of which the optimal configuration would later be implemented into the 1st generation of the PneuScooter. The 3- and 4-wheel configurations were tested as were different size pneumatic radial piston motors: PTM Mechatronics PMO 1800 and PTM Mechatronics PMO 3600 [69]; airline tubing sizes: 6.35 mm and 9.53 mm diameters; operating pressures: 6.21 bar and 8.27 bar; and gear ratios: 1:1, 1:1.2, and 1.2:1. The different gear ratios were achieved by installing 36-, 43-, and 30-tooth sprockets to the motor output shaft, respectively.

The set up for optimization testing was performed on a double drum testing mechanism typically used for ISO 7176 Wheelchair Standards testing. A 100 kg weight was secured to the seat of the prototype to simulate the load on the mobility device when traveling with a user (Figure 5). The slats on the double drum were removed to simulate a flat, smooth surface, and the double drum was disconnected from its power source to allow the drums to freely rotate. The speed of the wheels was measured using a tachometer (Mitutoyo PH-200LC), and the airflow rate was measured using a digital flow meter (SMC, PFMB7501-N04-A). Constant operating air pressures of 6.21 bar and 8.27 bar were used via a constant air supply from the laboratory air source.

Figure 5: Proof of Concept Optimization Testing Set up

The optimization testing procedure involved driving the prototype forward on the double drums while adjusting the flow control valve such that the desired speed of the wheels was achieved. Wheel velocities started at 0.1 m/s and increased in increments of 0.1 m/s until the airflow rate reached 210 L/min (limit of the digital flow meter) or the maximum speed of prototype was reached. Airflow rates at each of the wheel velocities were recorded and later entered into a spreadsheet for analysis. Each test consisted of changing a single parameter or component and repeating the testing procedure. Table 4 provides a breakdown of the tests performed for each set of configurations. In addition to the optimization testing, dynamic stability testing was performed as described in ISO 7176-2: Determination of Dynamic Stability.

Table 4: Proof of Concept Prototype Component Configurations

Test	No. of wheels	Motor	Tubing, mm	Pressure, bar	No. of teeth
1	4	1800	6.35	6.21	30
2	4	1800	6.35	6.21	36
3	4	1800	9.53	6.21	30
4	4	1800	9.53	8.27	30
5	4	1800	9.53	6.21	36
6	4	1800	9.53	8.27	36
7	4	3600	6.35	6.21	30
8	4	3600	6.35	8.27	30
9	4	3600	6.35	6.21	36
10	4	3600	6.35	8.27	36
11	4	3600	9.53	6.21	30
12	4	3600	9.53	8.27	30
13	4	3600	9.53	6.21	36
14	4	3600	9.53	8.27	36
15	4	3600	9.53	6.21	43
16	4	3600	9.53	8.27	43
17	3	3600	9.53	6.21	Direct drive
18	3	3600	9.53	8.27	Direct drive

Theoretical distances were calculated from the optimization results using the proof of concept prototype’s wheel diameter of 24.94 cm and two 9 L HPA tanks at a pressure of 310 bar.

Calculations were performed using two HPA tanks due to the size of the tanks and amount of space available on board the prototype. The estimated distance of each of the different components and parameters were compared to determine the optimal configuration that provided the greatest range at the target speed of 1.4 m/s (average human walking speed). Equations 1-5 were used to calculate the theoretical distances using the following constants: air volume (V), wheel circumference (C) and wheel diameter (d); as well as the variables of speed (V_T) and air flow rate (F).

$$(\mathbf{310}\ \boldsymbol{bar})(\mathbf{18}\ \boldsymbol{L}) = (\mathbf{1.013}\ \boldsymbol{bar})(\boldsymbol{V})$$

Equation 1: Air volume at atmospheric pressure

$$\boldsymbol{V} = \frac{(\mathbf{310}\ \boldsymbol{bar})(\mathbf{18}\ \boldsymbol{L})}{\mathbf{1.013}\ \boldsymbol{bar}} = \mathbf{5580}\ \boldsymbol{L}$$

Equation 2: Air volume at atmospheric pressure (continued)

$$\boldsymbol{C} = \boldsymbol{\pi d} = \boldsymbol{\pi}(\mathbf{0.249}\boldsymbol{m}) = \mathbf{0.782}\boldsymbol{m}$$

Equation 3: Wheel circumference

$$\boldsymbol{RPM} = (\boldsymbol{V_T}) \times \frac{\mathbf{60}\boldsymbol{s}}{\mathbf{1}\boldsymbol{min}} \times \frac{\mathbf{1}}{\mathbf{0.782}\boldsymbol{m}} = \mathbf{76.73}\boldsymbol{V_T}$$

Equation 4: Revolutions per minute

$$\boldsymbol{Theoretical\ distance} = \frac{\boldsymbol{V} * \boldsymbol{RPM} * \boldsymbol{C}}{\boldsymbol{F}} = \frac{(\mathbf{5580}\ \boldsymbol{L})(\mathbf{76.73}\boldsymbol{V_T})(\mathbf{0.782}\boldsymbol{m})}{\boldsymbol{F}} = \mathbf{33.48} \times \mathbf{10^4}\,\frac{\boldsymbol{V_T}}{\boldsymbol{F}}$$

Equation 5: Theoretical distance

2.2.3 PneuScooter Development

The 1st generation PneuScooter was created with the system of the components determined from optimization testing of the proof of concept prototype. Several iterations of frame designs were created until there was a consensus within the research team as to which concept to pursue manufacturing. A 2nd generation PneuScooter was created to redesign the frame due to a catastrophic failure of the 1st generation's frame during the curb drop test of the ISO Wheelchair Standards testing. Final design criteria are listed in Table 5.

Table 5: PneuScooter Final Design Criteria

Design Criteria
1. Weight capacity of 135 kg
2. Maximum length of 120 cm and width of 60 cm
3. Have a minimum speed of 1.4 m/s
4. Single easily accessible port for refilling
5. Interchangeable seating system
6. No electronics

2.2.4 PneuScooter Range and Standards Testing

Range testing of the 1st generation PneuScooter was performed by driving the prototype around an indoor, rectangular track as defined in ISO 7176-2: Energy Consumption. The prototype was driven around the track in either the clockwise or counterclockwise direction for 5 laps; the direction of the prototype was then reversed and driven for another 5 laps. Testing started with the scooter traveling at a speed of 1.4 m/s and ended when the prototype's speed dropped below the minimum threshold speed of 0.5 m/s. Three different air tank configurations were tested, each 3 times to obtain an average. The testing configurations were 1 scuba tank (9 L total), 2 scuba tanks (18 L total), and 2 scuba tanks with the addition of a 1.44 L tank (19.44 L total) as an expansion chamber.

The evaluation of the safety, durability and maneuverability of the 1st generation PneuScooter was performed using the 2009 edition of the ISO 7176 Wheelchair Standards [70, 71]. The PneuScooter underwent the following tests: static and dynamic stability (Sections 1 and 2, respectively); effectiveness of brakes (Section 3); energy consumption (Section 4); maximum speed, acceleration, and deceleration (Section 6); impact and fatigue tests (Section 8); obstacle climbing ability (Section 10); and power and control systems (Section 14). A 100 kg test dummy was used to complete the testing procedures when required. Sections 4, 8 and 14 of the standards were modified from their original procedures to accommodate the pneumatic system. All other testing equipment and procedures conformed to the requirements set forth in the ISO 7176 Wheelchair Standards.

The results of ISO testing of electric mobility scooters previously tested at the research facility are presented for comparison with the 1st generation PneuScooter. Testing result averages of the electric PMD results were calculated for Sections 1, 3, 4, 6 and 10. Averages for Sections 2, 8 and 14 were not calculated because they were based on a numeric scale (Section 2) or pass/fail criteria (Sections 8 and 14). Averages for the electric mobility scooters were calculated using 4 different scooter models from 2 manufacturers with 3 identical scooters of each of the following models (N = 12): Pride Mobility Victory 10, Pride Mobility Gogo Elite, Golden Technologies Golden Companion I and Golden Technologies Golden Companion II.

2.3 Results

2.3.1 Proof of Concept Testing

The feasibility test resulted in the 4-wheel proof of concept prototype traveling 800 m, thus meeting the minimum travel distance (500 m) for compressed air to be considered a feasible alternative to batteries. As a result, optimization tests using the proof of concept prototype followed to determine an ideal configuration of components and parameters that would translate into the device traveling as far as possible while maintaining the capability to climb a 10° slope. The calculated results for the theoretical distance versus velocity from the optimization tests are presented in Appendix A. For both motor sizes, there was a negative linear trend such that as speed increased, range decreased. The higher gear ratios and larger airline tubing diameters increased maximum speed and distance values; there was no change in speed or distance capability between operating pressures. Although during dynamic stability testing, the prototype traveled up the slopes at a higher speed using the higher operating pressure.

After calculating the theoretical distances for each of the configurations, it was determined that a 3-wheel scooter with the PMO 3600 motor, gear ratio of 1:1.2, 9.53 mm tubing, and 8.27 bar operating pressure provided the greatest distance when traveling at a speed of 1.4 m/s. However, with this optimal configuration, the 3-wheel proof of concept prototype failed dynamic stability testing. As a result, the components and parameters of the optimization test 16 was utilized as the foundation for the design of the 1st generation PneuScooter. The results of the theoretical distance calculations are provided for test 16 in Figure 6.

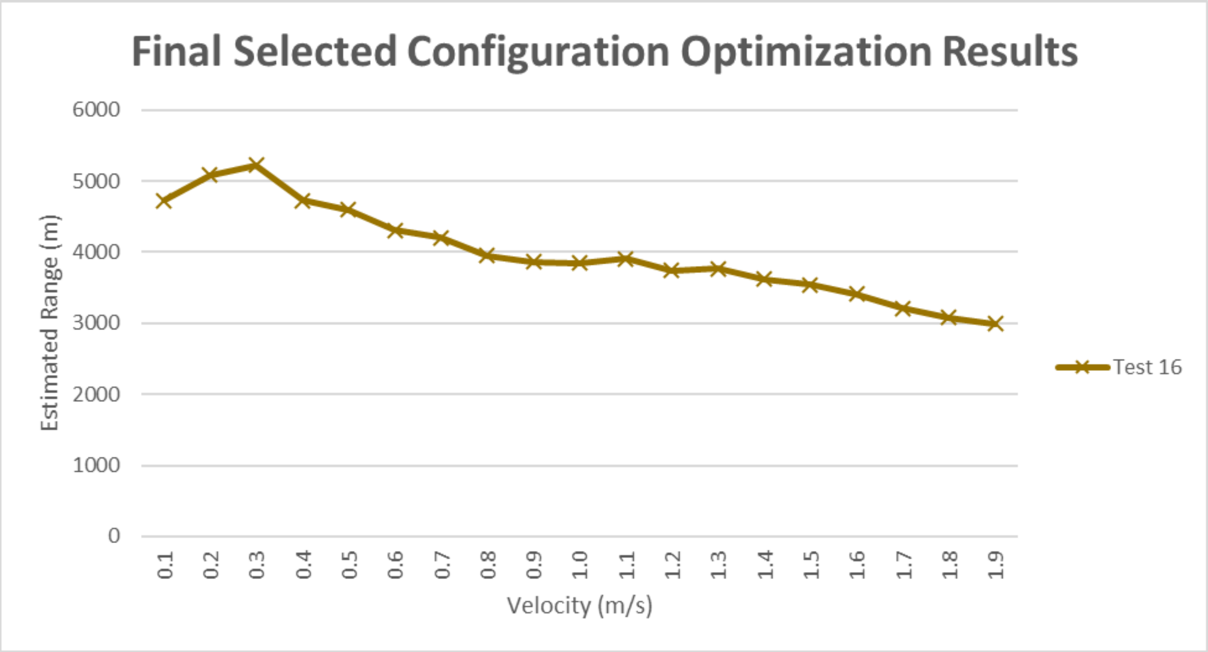


Figure 6: Final Selected Configuration Optimization Results

2.3.2 1st Generation PneuScooter Design

The 1st generation PneuScooter consisted of a 4-wheel mobility scooter designed with a custom frame made using 25.4 mm diameter, 1.65 mm wall thickness, 6061-T6 aluminum tubing (Figure 7). The design included a modular front steering assembly for simplified maintenance, easily removable seat allowing for multiple seat types, and an easily accessible charge port to recharge both air tanks at once.

Figure 7: PneuScooter Concept (left) and Prototype (right)

2.3.3 1st Generation PneuScooter Performance Testing

The results of the range testing for the 1st generation revealed that the scooter traveled an average of 1267 m using 1 scuba tank (9 L), 2762 m using 2 scuba tanks (18 L), and 3150 m using 2 scuba tanks and a 1.44 L tank (19.44 L) as an expansion chamber at an ambient temperature of 21°C. In the slope climbing tests, the 1st generation passed both scenarios when using the optimal configuration of components. When the gear ratio was increased to 1:1.4, the prototype was unable to pass either slope testing scenarios. As a result, the prototype's gear ratio was set to 1:1.2.

2.3.4 2nd Generation PneuScooter Design

Although the 1st generation PneuScooter performed well during the range and slope tests, the frame experienced a class III failure during the curb drop test of the ISO standards testing (Figure 8). As a result of the failure, finite element analysis (FEA) was performed using SolidWorks Simulation on the 1st and 2nd generation frames (Figure 9). The results of the FEA for the 1st generation frame nicely matched with the location of failure from the curb drop test. FEA was then used during the redesign of the frame for the 2nd generation to reduce the likelihood of a future failure. The redesign resulted in the addition of a 2nd tubular frame rail around the outer perimeter, an additional frame tube running down the center and vertical supports between the top and bottom frame rail. The 2nd generation PneuScooter frame is shown in Figure 10 with modifications shown in red.

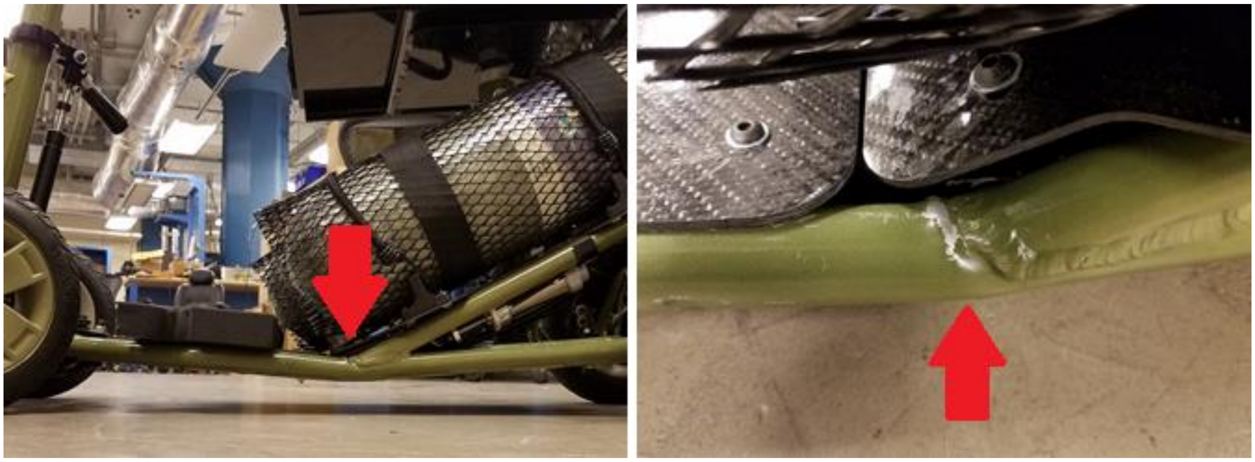


Figure 8: PneuScooter Frame Failure

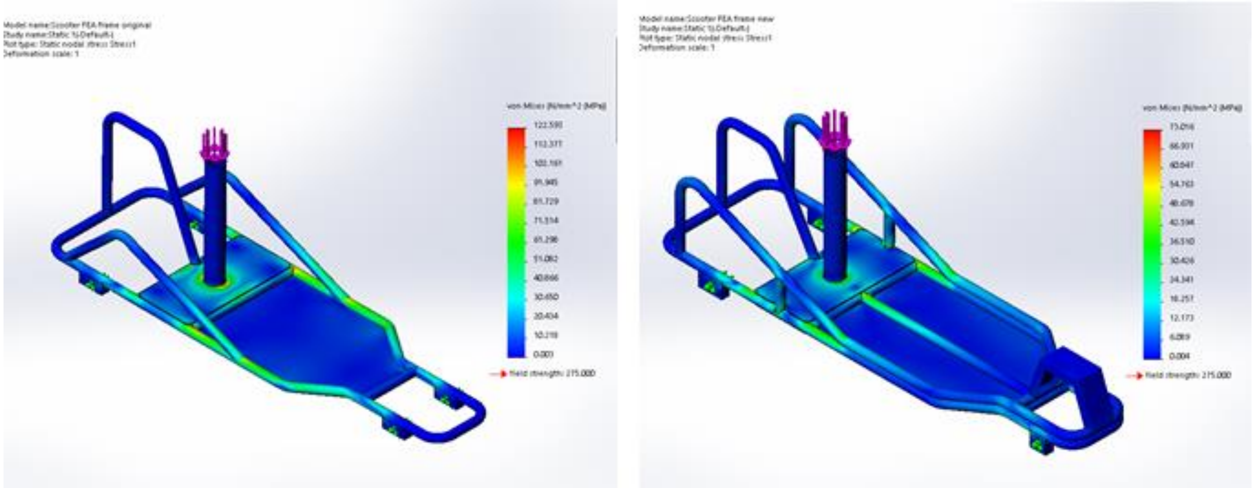


Figure 9: FEA results: 1st Generation (left) and 2nd Generation (right)

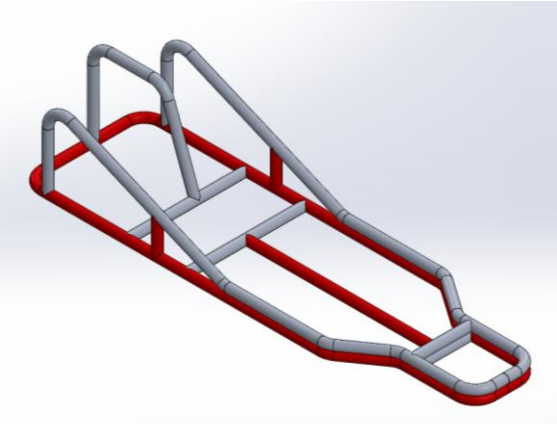


Figure 10: 2nd Generation PneuScooter Frame

The 2^{nd} generation of the PneuScooter comprises of a configuration for long-term care facilities (LTC) and a configuration for big-box (BB) stores. The PneuScooter LTC features a pivoting front axle, adjustable tiller and rehab style seat. The PneuScooter BB adds an air activated reverse horn and a basket to the front of the device to carry groceries and/or supplies. Conceptual designs for the PneuScooter LTC and PneuScooter BB are shown in Figure 11 and Figure 12, respectively. A manufactured prototype of PneuScooter BB is shown in figure Figure 13.

Figure 11: PneuScooter LTC Concept Design

Figure 12: PneuScooter BB Concept Design

Figure 13: PneuScooter BB Manufactured Prototype

2.3.5 ISO Standards Testing

Static stability results (Section 1) for the PneuScooter and electric mobility scooters are shown in Table 6. The PneuScooter is as stable or more stable than electric scooters in all stability directions except when traveling forward with the front wheels unlocked. Testing of the dynamic stability tests (Section 2) resulted in a score of 3 (no tip: at least 3 wheels remain on the test plane at all times) for all tests. The results of brake effectiveness testing (Section 3) are provided in Table 7. The PneuScooter traveled a total distance of 5.07 km for the energy consumption test (Section

4) using 2 fully filled air tanks pressurized at 310 bar compared to the calculated theoretical distance of 25 km for electric mobility scooters. Test results for maximum speed, acceleration and deceleration (Section 6) are shown in Table 8. The 1st generation PneuScooter passed all impact and static tests until experiencing a class III failure during fatigue testing of the curb drop test (Section 8) (Figure 8). Fatigue testing of the 2nd generation PneuScooter passed. An image of the 2nd generation PneuScooter during double drum testing is shown in Figure 14. Obstacle climbing ability (Section 10) results are provided in Table 14. The PneuScooter passed all the applicable power and control systems requirements (Section 14) with a 2 N force needed to operate the controls.

Figure 14: 2nd Generation PneuScooter Double Drum Testing

Table 6: PneuScooter Static Stability (Section 1)

Stability Direction		**Tipping Angle (degrees)**	
		PneuScooter	Electric
Forward	Front Wheels Locked	N/A	41.8
	Front Wheels Unlocked	30.0	40.0
Rearward	Rear Wheels Locked	21.0	13.5
	Rear Wheels Unlocked	26.0	14.5
	Anti-Tip Devices*	N/A	12.4
Sideways	Left	20.0	19.9
	Right	22.0	18.8
*The PneuScooter does not feature anti-tip devices. N/A indicates the device is not applicable in that configuration.			

Table 7: PneuScooter Effectiveness of Brakes (Section 3)

		Average Braking Distance (m)					
		PneuScooter			**Electric**		
Inclination	Direction	Normal	Reverse	Emergency	Normal	Reverse	Emergency
0 degrees	Forward	1.27	0.62	1.47	1.83	1.46	1.62
	Reverse	0.31	0.11	0.54	0.79	0.59	0.76
3 degrees	Forward	2.63	1.65	3.00	2.19	1.91	2.04
	Reverse	0.70	0.15	0.91	1.12	0.83	1.05
6 degrees	Forward	2.18	1.81	2.85	2.81	2.62	2.59
	Reverse	1.39	0.35	1.57	1.35	1.09	1.27
10 degrees	Forward	3.20	2.74	3.66	3.91	3.65	3.81
	Reverse	2.05	0.43	2.32	1.75	1.70	1.64

Table 8: PneuScooter Maximum Speed, Acceleration and Deceleration (Section 6)

Maximum speed (m/s)	**PneuScooter**	**Electric**
Forwards horizontal	1.66	2.24
Forwards downhill 3° ramp	2.29	2.35
Forwards uphill 3° ramp	1.14	1.90
Rearwards horizontal	1.03	1.11
Acceleration (m/s^2)		
Overall	0.90	0.63
Maximum	0.97	1.65
Deceleration (m/s^2)		
Overall	1.75	1.47
Maximum	1.83	2.28

Table 9: PneuScooter Obstacle Climbing Ability (Section 10)

	Obstacle Ht. (mm)	
Obstacle climbing	**PneuScooter**	**Electric**
Forwards, no run-up	30	60
Backwards, no run-up	20	31
Forwards, .5m run-up	65	84
Backwards, .5m run-up	25	39
Obstacle descending		
Forwards, 1m run-up	65	N/A
Backwards, 1m run-up, slow speed	25	N/A

2.4 Discussion

The development of new technologies for PMD users is important to continue advancing the field and improving the lives of those with disabilities. Novel technologies such as the pneumatic technology developed from this research provides solutions to many of the current issues with electric PMDs as well as opens doors to possibilities that are impossible due to limitations of current technologies. For instance, pneumatic PMDs are less vulnerable to environmental hazards such as dirt, heat and moisture [72, 73]. Their ability to operate in water or moisture-rich areas and in environments that pose fire/explosion risks (e.g. oxygen-rich environments) are clear advantages over electric PMDs. They also open opportunities for mobility at beaches and water parks as well as other wet environments such as those with high relative humidity of which pneumatic PMDs should offer much higher reliability and longevity than electric PMDs [74]. Pneumatic technology could also serve as a potential solution for power mobility issues in less-resourced countries. Other inherent advantages of pneumatic PMDs are the ability to be recharged quickly, nearly an unlimited number of times; the system’s simple design decreases the likelihood of breakdowns and makes for easier troubleshooting; and the longevity of pneumatic components requires little maintenance, thus decreasing the probability of the device to be inoperable for long periods of time.

Some common concerns that may impact the adoption of pneumatic PMDs are their limited driving range, noise and safety. The limited driving range of PMDs is a concern for active users who use their device outside of the home. The current lack of recharging stations within the community raises concerns for the user becoming stranded and unable to recharge their tanks. As a result, pneumatic PMDs are more suited for locations where the devices would remain around a centralized location such as big-box and retail stores, hospitals and long-term care facilities where a recharging station would be in close proximity at all times. Additionally, the necessary compressor to recharge the pneumatic PMDs are commonly available at sporting goods stores that charge paintball tanks, dive shops and fire or emergency medicine stations. Thus, with the availability of recharging stations around the community, pneumatic PMDs could be used by all types of users.

The noise generated by a pneumatic PMD occurs when the air is exhausted out of the system. On average, typical noise levels generated by pneumatic motors is around 77 dB. The noise level of the radial piston motors used in the pneumatic PMDs in this study is roughly 60 dB [69]. In comparison, an electric PMD operates around a noise level of 58 dB. The noise of a pneumatic PMD can be decreased further with the addition of a muffler as well as changing the location of the exhaust on the device. In terms of safety, pneumatic components use no hazardous materials and meet both explosion protection and machine safety requirements because they do not generate magnetic interference [75]. Furthermore, the HPA tanks are commonly used by firefighters and scuba divers, and are required to be hydro-tested for safety every 5 years [76].

2.5 Conclusion

The use of pneumatic technology in powered mobility devices as an alternative to battery technologies is confirmed. The performance and ISO Wheelchair Standards test results as well as the numerous advantages of pneumatic technology provides adequate evidence for their success in real-world environments as well as serve as a competitor to battery powered mobility devices.

3.0 Design of The Pneumatic-Powered Wheelchair

3.1 Introduction

This research focused on incorporating the pneumatic technology developed from previous research into a powered wheelchair driven with a joystick. The design of the pneumatic-powered wheelchair, the PneuChair, began with conceptual designs driven by the specifications of Group 2 electric-powered wheelchairs. A prototype of the final design was manufactured and tested using ISO 7176 Wheelchair Standards. The results of the standards testing were compared to those of Group 2 electric-powered wheelchairs. Two focus groups were also conducted: the 1st focus group gathered feedback on the PneuChair's conceptual design and the 2nd focus group gathered feedback about individuals' experience with the PneuChair at a wheelchair accessible waterpark.

3.2 Methods

3.2.1 PneuChair Development

The design and development of the PneuChair began with the modification of an electric powered wheelchair by removing its batteries and electrical components. The early prototype (Figure 15) allowed for a better understanding of how the use of the pneumatic power system effected the driving characteristics of the wheelchair. The prototype’s use of two motors to travel forwards, backwards, left, right and any combination thereof required a more complex configuration of hoses, valves and fittings than the PneuScooter. Thus, the prototype served as a test rig for testing different methods to effectively be able to control the wheelchair with the use of a joystick. In addition to controlling the motors, a pneumatically operated braking system was developed such that the brakes would automatically disengage when the prototype began to move and reengage when the joystick returned to its neutral position.

Figure 15: PneuChair Early Prototype

Once the mechanics of the control system were determined, several conceptual designs were created based on specifications outlined by Medicare for a Group 2 electric powered wheelchair. Group 2 specification requirements were defined as a device having a maximum length of 122 cm, maximum width of 86.4 cm, minimum obstacle height climbing ability of 4 cm, minimum top speed on a flat surface of 1.34 m/s and a minimum dynamic incline stability of 6° [77, 78]. Fortunately, the development of the PneuScooter aided in the overall progress of the PneuChair wherein the same components were used (i.e. airline diameter, radial piston air motors, regulators, valves, etc.). Lastly, a prototype of the final conceptual design was manufactured based on the design criteria listed in Table 10.

Table 10: PneuChair Final Design Criteria

Design Criteria
1. Maximum length of 122 cm and width of 86.4 cm
2. Minimum obstacle height climbing ability of 4 cm
3. Minimum top speed on a flat surface of 1.4 m/s
4. Minimum dynamic incline stability of 6°
5. Rear-wheel drive, Joystick controlled
6. Waterproof (no electronics)
7. Weight capacity of 100 kg
8. Single easily accessible port for refilling

3.2.2 ISO Standards Testing

The PneuChair's durability, safety and maneuverability was evaluated by conducting the tests outlined in the ISO 7176 Wheelchair Standards tests [70, 71]. Sections 1, 2, 3 and 6 tests were completed as a required in the standards. Sections 4, 8 and 14 were modified to accommodate the pneumatic-powered system of the PneuChair. A 100 kg test dummy was used to complete the testing procedures where required, all other testing equipment conformed to the requirements set forth in the standards. The test results were compared with Group 2 electric powered wheelchair test results previously tested at the research facility. Averages were calculated for sections 1, 3, 4, 6 and 10 for the Group 2 powered wheelchairs using 4 different wheelchairs from 3 manufacturers. 3 identical wheelchairs of each of the following were tested (N = 12): Pride Mobility Jazzy Select Elite, Pride Mobility Jazzy Select 6, Invacare Pronto M41, and the Hoveround MPV5. Averages for sections 2, 8 and 14 were not calculated due to either being based on a numeric scale or pass/fail criteria.

3.2.3 Focus Groups

The design of the PneuChair utilized the participatory action design approach, where feedback is gathered from users throughout the development process. As a result, two focus groups were conducted. The purpose of the 1st focus group was to gather feedback about the PneuChair's conceptual design. During the focus group, multiple conceptual designs were presented, demos were performed to demonstrate recharging the device and participants were asked to provide feedback in a group discussion. Participants were eligible if they were 18 years of age or older and either had their own mobility device, used the mobility scooters provided by convenience/grocery/big-box stores or were rehabilitation professionals involved in the provision of wheeled mobility devices. The purpose of the 2nd focus group was to gather feedback from individuals who used the PneuChair during a visit at Morgan's Inspiration Island, a wheelchair accessible water park located in San Antonio, Texas. A phone conference was performed with the participants due to the distance between the research facility and Morgan's Inspiration Island. Participants were eligible to participate if they were 18 years of age or older and either operated or assisted with operating and/or maintaining the PneuChair. Ethical approval for the focus groups were obtained from the institutional review board of the University of Pittsburgh. All participants were asked to provide informed consent prior to enrollment in the focus group.

3.3 Results

3.3.1 PneuChair Design

The final design of the PneuChair (Figure 16) comprised of a rear-wheel drive power wheelchair with a custom-designed aluminum frame, a pneumatic joystick (DEL Hydraulics, pneumatic feathering joystick), two rotary piston air motors (PTM Mechatronics PMO 1800), 8 mm airline tubing, two HPA tanks, 8.27 bar operating pressure and a gear ratio of 1:1. The braking system was designed as a failsafe with the intent that the brakes were engaged at times when the joystick is in its neutral position or if the PneuChair loses pressure or runs out of air. A spring-engaged pneumatic actuator engages the brakes and is released via air pressure when the joystick is moved from its neutral position. A charge port located on the rear of the device allows both tanks to be refilled simultaneously while remaining inside the device. Lastly for simplicity, a manual wheelchair frame was chosen as the seating system.

Figure 16: PneuChair Concept Design (left) and Manufactured Prototype (right)

3.3.2 ISO Standards Testing

The results of static stability (Section 1) are shown in Table 11 for the PneuChair and Group 2 electric powered wheelchairs. The higher the angle value, the more stable the device. The PneuChair received a score of 3 (no tip: at least 3 wheels remain on the test plane at all times) for all dynamic stability tests (Section 2) with the exception of when the brakes were applied when traveling backwards on a flat surface and slopes of 3°, 6° and 10°. For these tests, the PneuChair received a score of 2 (transient tip: less than 3 wheels remain on the test plane at some point during the test and then drop back onto the test plane) due to the front casters lifting off the surface. In comparison, all Group 2 wheelchairs received scores of 3 for the dynamic stability tests. Effectiveness of brakes testing (Section 3) results are provided in Table 12. Electric wheelchair parking brake and running break effectiveness data for the 6° and 10° tests were not available for comparison.

Table 11: PneuChair Static Stability (Section 1)

Stability Direction		**Tipping Angle (degrees)**			
		PneuChair		**Electric**	
		Least Stable	Most Stable	Least Stable	Most Stable
Forward	Front Wheels Locked	N/A	N/A	N/A	N/A
	Front Wheels Unlocked	33.7	N/A	23.7	27.1
Rearward	Rear Wheels Locked	12.6	N/A	N/A	N/A
	Rear Wheels Unlocked	17.7	N/A	23.0	32.0
	Anti-Tip Devices*	29.4	N/A	N/A	N/A
Sideways	Left	24.3	N/A	19.2	22.2
	Right	23	N/A	18.8	21.2

*Least Stable and Most Stable refer to the positioning of the anti-tip devices. The PneuChair anti-tip devices do not have multiple positions, thus only least stable values are recorded. N/A indicates not all devices are applicable in that configuration.

Table 12: PneuChair Effectiveness of Running Brakes (Section 3)

		Average Braking Distance (m)					
		PneuChair			**Electric**		
Inclination	Direction	Normal	Reverse	Emergency	Normal	Reverse	Emergency
0 degrees	Forward	1.37	0.78	1.78	1.45	1.25	1.35
	Reverse	0.60	0.35	0.85	0.57	0.41	0.49
3 degrees	Forward	3.39	1.46	2.69	1.56	1.36	1.51
	Reverse	1.58	0.57	1.81	0.54	0.41	0.48
6 degrees	Forward	6.49	3.20	6.14	N/A	N/A	N/A
	Reverse	2.17	1.71	2.88	N/A	N/A	N/A
10 degrees	Forward	8.64	4.39	9.52	N/A	N/A	N/A
	Reverse	*	*	*	N/A	N/A	N/A
*Not performed, slide/spin in this direction							

The energy consumption test (Section 4) for the PneuChair resulted in a total travel distance of 3.2 km using 2 fully filled air tanks at 310 bar. Unlike the calculated theoretical distance of 19.9 km for the Group 2 wheelchairs (actual distance is often considerably less), the travel distance of the PneuChair was determined using a real-world test. Test results for maximum speed, acceleration and deceleration (Section 6) are provided in Table 13. The PneuChair passed all static, impact and fatigue strength tests (Section 8) with the exception of the armrests, which resulted in permanent deformation when tested in the static strength portion of the test. The armrests are part of the manual wheelchair frame that was used for the seating system of the PneuChair and were not originally intended for use on a powered wheelchair, thus the forces they were required to withstand were higher than expected. All Group 2 wheelchairs passed Section 8 testing. The result of the obstacle climbing tests (Section 10) are provided in Table 14. The PneuChair passed all the applicable power and control systems requirements (Section 14) apart from not having a hose connection diagram. The necessary force to operate the PneuChair joystick was 82 N.

Table 13: PneuChair Maximum Speed, Acceleration and Deceleration (Section 6)

Maximum speed (m/s)	**PneuChair**	**Electric**
Forwards horizontal	1.16	1.91
Forwards downhill 3° ramp	2.28	1.95
Forwards uphill 3° ramp	0.97	1.72
Rearwards horizontal	1.23	0.91
Acceleration (m/s^2)		
Overall	0.632	1.29
Maximum	0.79	1.41
Deceleration (m/s^2)		
Overall	1.24	1.55
Maximum	1.99	1.57

Table 14: PneuChair Obstacle Climbing Ability (Section 10)

	Obstacle Ht. (mm)	
Obstacle climbing	**PneuChair**	**Electric**
Forwards, no run-up	18	36
Backwards, no run-up	18	23
Forwards, .5m run-up	30	60
Backwards, .5m run-up	32	36
Obstacle descending		
Forwards, 1m run-up	35	60
Backwards, 1m run-up, slow speed	35	36

3.3.3 Focus Groups

The results of the conceptual design focus group provided useful feedback and raised several important points with 12 individuals participating with an average age of 50.3 (SD 11.8) years. Several participants expressed a desire to use the PneuChair outside the home to go shopping (n = 3, 25%) and in wet environments such as a beach or waterpark (n = 5, 41.7%). Three participants (25%) stated they had problems charging their electric PMD, and two (16.7%) expressed dissatisfaction with the electric systems of their electric PMDs. Seven participants

(58.3%) expressed interest in using the PneuChair. Some of the major design considerations discussed included range capability of the device, the need for seat tilt, the addition of a secondary or failsafe brake and color combinations. Other suggestions included having an option for an attendant control, postural supports, harness for users with limited trunk control or spasticity, addition of push handles and the removal of sharp edges that may injure the user or caregivers. After being presented with a demonstration of the process for recharging the air tanks, none of the participants felt the recharging process was more complex than charging an electric PMD.

The feedback received from the participants who used or had experience with the PneuChair at Morgan's Inspiration Island was focused around the control and seating system. They stated approximately 70% of the guests who visited the park and wanted to use the PneuChair were unable to independently operate the device due to the amount of force needed to operate the joystick. As a result, 20-30% of the users who were able to operate the PneuChair were individuals with paraplegia and could self-propel a manual wheelchair. Other issues mentioned were lack of consistency with the devices being able to drive straight as well as difficulty making the device go in reverse. In terms of the seating system, the lack of tilt, postural supports and a headrest limited the users who could use the device to those with good trunk and/or upper extremity strength. On average, each guest used the PneuChair for 2-4 hours before requiring a refill. Lastly, there were no reports of breakdowns or repairs needed over the 3 months the device was in operation nor were there issues with the PneuChair's range limitation.

3.4 Discussion

The development of a novel, alternative power source for powered wheelchairs resulted in the creation of the PneuChair. The passing and results of the ISO Wheelchair Standards indicate that the use of pneumatic technology is not only a feasible replacement for electric PMDs but also a potential competitor. When comparing average weights to its respective electric PMD counterparts, the PneuChair is 34.6% lighter (Average Group 2 wheelchair weight 81.8 kg versus PneuChair weight 53.5 mg). The lighter weight nature of pneumatic PMDs allows for easier transport in both vehicles and airplanes and could prevent the need for purchasing of an expensive, highly modified accessible vehicle because the device could be lifted into the rear of a vehicle.

The PneuChair met the minimum speed requirement of 1.4 m/s with a maximum speed of 1.56 m/s. However, the maximum speed could be adjusted based on user needs and environment. As for recharging time, the PneuChair is capable of recharging in under 10 minutes, yet the overall recharge time is dependent on the recharging method. There are several recharging methods and the selected one is dependent on several factors including the duration of time the device needs to be operational, number of devices at the location, number of devices that are available for use at a given time and distance the device travels per use. These factors determine the air compressor size as well as whether or not an air storage system is needed.

In general, there are 3 different methods for recharging of the pneumatic PMDs. The 1st method is to recharge the device via direct connection to the air compressor. In this case, the size of the compressor determines the overall time to refill and is typically the slowest of the 3 methods requiring between 20 and 120 minutes. The 2nd method is to have a recharging station that consists of a single large storage tank or multiple smaller tanks that are connected to a compressor that constantly maintains the storage tank pressure at 310 bar. As a result, the stored air is able to be transferred directly to the HPA tanks on board the device in as little as 10 minutes. Lastly, the 3rd method is identical to the 2nd with the exception of the air compressor. For this method, a mobile air compressor unit could visit the home or site to refill the tanks or a bottle service could be used to pick up the empty tank(s) and replace them with filled tanks. For method 3, the number of recharges would depend on the size and number of storage tanks. For all methods, the PMD is connected to the compressor or storage tanks via a quick disconnect hose, similar to how electric PMDs are plugged in to recharge.

Each of the previously mentioned recharging methods are best suited for different scenarios. For example, the 2nd method is best utilized at locations where 3 or more devices are used and remain at a centralized location such as a grocery/big-box store or long-term care facility. Additionally, this method is advantageous at locations where the devices would be in constant use throughout the day because they could be quickly recharged and put back into use unlike electric devices that require hours to recharge. The 1st and 3rd methods are most likely beneficial for use in the home or at locations where the PneuChair wouldn't travel long distances or be in use for long periods of time.

The ISO Wheelchair Standards test results were comparable to Group 2 electric powered wheelchairs. Although the range of the PneuChair is a concern, the capability of pneumatic PMDs to be recharged in minutes is superior when considering electric powered wheelchairs require up to 8 hours to recharge. This advantage was justified during the five-month period that the PneuChair was in use at Morgan’s Inspiration Island, as guests had the devices recharged when running low on air capacity.

As a novel device, much of the development of the PneuChair was focused towards implementing the pneumatic technology into the base of the device rather than the seating system.

Therefore, it was expected that there would be issues with the controls and seating systems, as was confirmed by the feedback received during the experience focus group. As a result, future work will consist of the development of a low force joystick and rehab style seating system with the addition of pneumatic-powered seating functions, lateral supports and headrest.

3.5 Conclusion

The impact of using pneumatic technologies in powered mobility devices has implications in numerous markets. Locations such as hospitals, long-term care facilities, supermarkets and airports, where there are fleets of powered mobility devices, could greatly benefit from pneumatic-powered mobility devices. At these locations, battery maintenance is essential yet difficult to maintain, resulting in devices that are in need of repair and unusable for long periods of time. Other possibilities where pneumatic-powered mobility devices may be superior are during emergency or disaster situations, such as after earthquakes, hurricanes or tornadoes, when electricity is unavailable and/or flooding or wet environments render electric-powered mobility devices useless. The ability of the PneuChair to operate in a wide array of settings not only offers an alternative to electric-powered mobility devices for everyday use, but also opens the door for activities that are otherwise currently impossible.

4.0 Usability Evaluation of Pneumatic-Powered Shopping Carts

4.1 Introduction

The 2014 Americans with Disabilities report conducted by the US Census Bureau found that individuals who had difficulty walking greater than 400 m also had difficulty performing Instrumental Activities of Daily Living, the most common being going outside to run errands [3]. Shopping at a retail store is one example that often requires walking long distances. Fortunately, many retail stores have motorized shopping carts available for individuals to use whether they have a temporary or permanent physical disability that results in difficulty walking throughout the store or using a regular cart [79].

The motorized carts are available on a first-come, first-served basis and usually parked at the store's entrance. The number of carts at each store varies based on the store's daily number of customers and size. The motorized carts are powered by rechargeable batteries and should be charged overnight, every night as they require at least 5 hours to fully recharge yet are expected to run up to 12 hours [80, 81]. Moreover, they should be plugged into charge when not in use because a fully discharged battery could take up to 20 hours to fully recharge [80]. Their long and frequent recharge demands often results in extended periods of time for which they are inoperable, resulting in an inconvenience for the customer.

The purpose of this study was to gain an understanding of how the motorized carts are used, pilot test a pneumatic-powered shopping cart to identify areas where it could be improved, investigate whether certain user demographics chose to use the pneumatic-powered carts versus the battery-powered carts and determine whether battery-powered carts could feasibly be replaced by pneumatic-powered carts [28, 82, 83].

4.2 Methods

4.2.1 Prototype Development

The pneumatic-powered shopping cart developed for this study was based on previous research of a pneumatic-powered mobility scooter for personal use [37]. As a result, the personal mobility scooter lacked several essential features necessary for use in a retail store setting. Thus, prior to the study launch, several modifications were needed for the pneumatic-powered cart to be useful. Upon receiving approval from the participating site leadership of the modified designs, three pneumatic-powered carts were created for the study. A list of the modifications is shown below:

- Restrict the speed setting of the pneumatic-powered cart to 0.9 m/s and eliminate the ability of the user to change maximum speeds.
- Install a whistle/tone that sounds when the cart travels in reverse and limit the reverse operating speed to half of the forward speed.
- Incorporate an air pressure indicator decal using red/yellow/green indicator bars indicate when the air pressure needs recharged – at the line between red/yellow, a note should indicate recharge before use.
- Install slip resistant surface on the foot platform.

- Guard front pinch points associated with the tiller.
- Replace the seat with one that is durable and can easily be cleaned/sanitized.
- Confirm that the seat height is equal to or less than 61 cm from the floor.
- Implement a basket and confirm its weight capacity is 68 kg.
- Confirm that the total payload capacity of the cart is 295 kg.

4.2.2 Study Design

A mixed methods research design was used in which quantitative data of the pneumatic-powered cart's runtime and distance driven was recorded in combination with qualitative data gathered via an online survey about the individual's shopping characteristics and experience using the motorized shopping carts. Ethical approval was obtained from the Institutional Review Board of the University of Pittsburgh.

4.2.3 Procedure

A member of the research team was on-site while the pneumatic-powered shopping carts were available for use. The researcher answered questions participants had about the study or how the pneumatic-powered cart operated, provided a mobile tablet for the participant to use if they chose to complete the survey in person and monitored the air pressure of each pneumatic-powered cart throughout the day to ensure that the cart's air pressure would not run too low and risk the cart running out of air while in use. When a researcher was not present, the pneumatic-powered carts were placed in a storage area as to prevent customers from using them.

The pneumatic-powered carts were recharged if their air pressure was below 138 bar after a participant was finished using it. A recharging unit was installed at the participating site and consisted of a Bauer DiveMate 7.5 HP air compressor (August Industries Inc., DMT08/E1) and a 4 tank 310 bar air storage system (August Industries Inc., 4500/4R). The air storage system allowed for the recharging of three pneumatic-powered carts prior to the compressor needing to be turned on to refill the storage system. Each time a pneumatic-powered cart was recharged, the researcher noted the date, time and which of the three pneumatic-powered carts was recharged.

4.2.4 Participants and Study Location

Individuals who visited the participating site were able to use the air or electric-powered carts. After individuals were finished using either of the motorized carts, a researcher approached them asking if they would like to complete the online survey. If they agreed, the individuals were given the option to either complete the survey in person via the use of a mobile tablet or were given a business card with a QR code and web link to complete the online survey at their own convenience. Participants were reimbursed with a $25 E-gift card if they met the inclusion criteria and completed the online survey. Criteria for inclusion for participants to take the online survey were: must have been 18 years or older, must have used a motorized shopping cart within the past seven days and be able to speak and comprehend English. The goal was to receive completed surveys from a total of 50 participants. The participating site was the Waterfront Giant Eagle Grocery Store in Homestead, Pennsylvania.

4.2.5 Data Collection and Analysis

Qualitative data were collected via a project specific online survey (Appendix B) using the University of Pittsburgh Qualtrics Survey System. The survey provided informed consent and screened participants for their eligibility to participate in completing the survey. The survey consisted of 29 questions asking about the participant's demographics, shopping experience and experience using one of the motorized shopping carts. Descriptive statistics were reported using frequency counts and percentages for each multiple-choice item. Open-ended responses were examined to identify overall patterns and themes, as well as unique suggestions for improvements to both types of motorized carts. Quantitative data collection was performed using a bicycle speedometer (SUAOKI, B01E3NRE30) mounted on each pneumatic-powered cart to collect runtime and distance driven. The frequency of recharges for the pneumatic-powered carts were also noted.

K-Means clustering analysis was performed to identify groups of individuals with similar demographics who chose to use the pneumatic-powered carts versus the electric-powered carts based on their responses to survey questions. The decision for how many clusters to specify for the model when performing the K-Means analysis was determined using a combination of the elbow and silhouette methods as well as ANOVA tests. The elbow method calculates the total within cluster sum of square (wss) for different values of k. For example, k varying from 2 to 10 clusters. A scree plot of wss versus clusters k was plotted to determine the approximate number of clusters based on the location of where the bend or "elbow" of the curve occurs. Next, the silhouette method was used to evaluate the cluster quality and further narrow down the number of clusters to perform the K-Means analysis. The silhouette method measures how far the clusters are from each other and how tight they are within. Lastly, ANOVA tests provided p-values and F statistics and determined the final number of clusters analyzed. IBM SPSS Statistics Version 26 was used for all statistical tests with a significance level of 0.05.

4.3 Results

4.3.1 Prototype Design

Modifications to the design of the previously developed pneumatic-powered mobility scooter were completed and successfully implemented into the new design of the pneumatic-powered cart. The frame was changed to accommodate a large basket on the front of the cart, the steering system was modified to decrease the amount of sweep the tiller moved when steering, a brake release was implemented to allow the cart to be freely pushed, shrouds were created to guard pinch points and prevent unwanted tampering with the air tank valves and an air horn was added to alert others when the cart was moving in reverse. The participating site leadership approved of the modifications and three pneumatic-powered carts were created (Figure 17).

Figure 17: Pneumatic-powered Cart Prototypes

4.3.2 Survey Responses

A total of 65 individuals provided informed consent. Figure 18 provides an exclusion diagram showing inclusion of 60 participants who completed the survey. Table 15 displays demographic characteristics of the participants. Average age was 41.2 (SD 18.5, range 21-86) years.

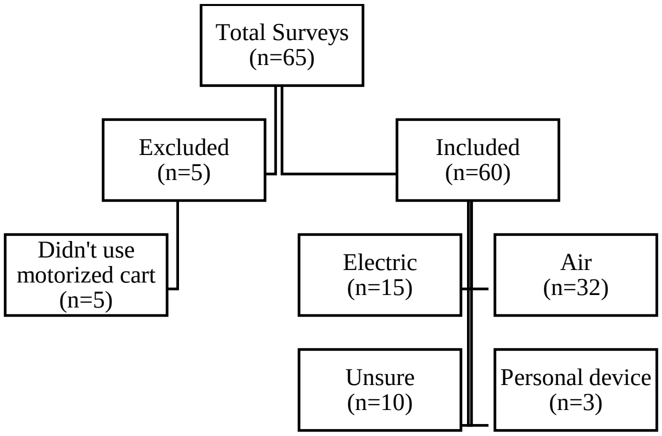
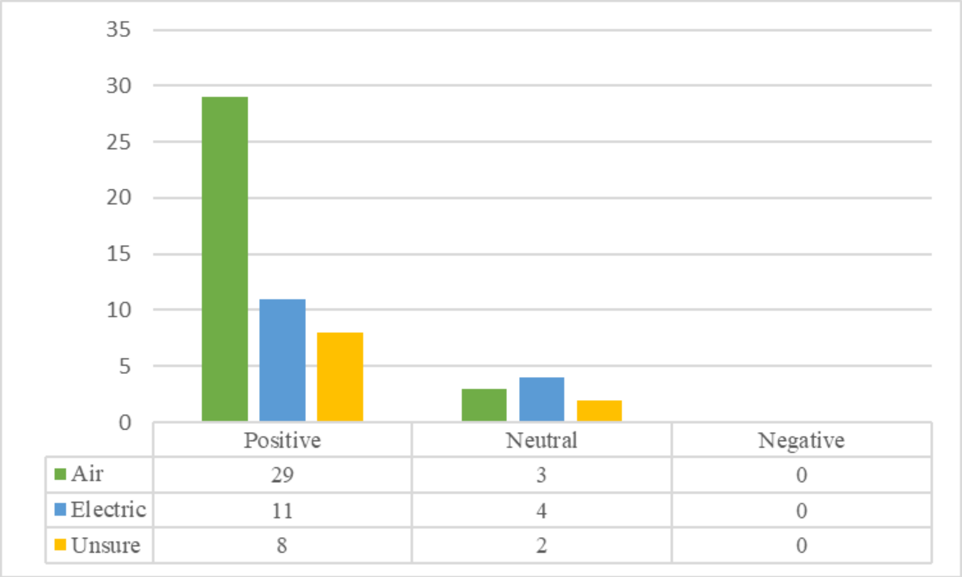


Figure 18: Study Participant Exclusion Diagram

Table 15: Participant Demographics

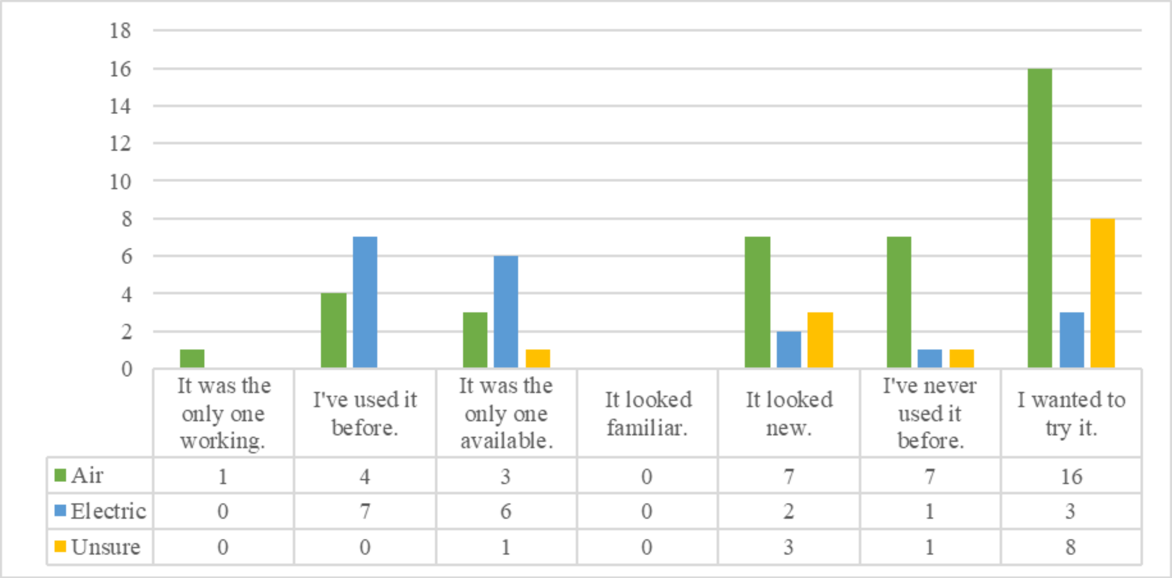
Gender	n	%
Female	35	58.3
Male	25	41.7
Ethnicity		
American Indian or Alaska Native	1	1.7
Black or African-American	11	18.3
White	40	66.7
Other	8	13.3
Veteran		
Yes	2	3.3
No	56	93.3
Prefer not to say	2	3.3
Age		
18-26	20	33.3
27-34	2	3.3
35-54	19	31.7
55-64	8	13.3
65 or over	11	18.3
Weight		
100-250 pounds (45-110 kg)	41	68.3
250-400 pounds (110-180 kg)	19	31.7
Personally own a mobility device		
Yes, cane or walker	20	33.3
Yes, manual wheelchair	8	13.3
Yes, power scooter	2	3.3
Yes, power wheelchair	3	5.0
No, I do not own a mobility device	27	45.0

A large majority of the participants' experience using the motorized shopping carts was positive (n=48, 84.2%) with some having a neutral experience (n=9, 15.8%) and none having a negative experience (Figure 19). Specifically, participants who responded they used a pneumatic-powered cart (n=29, 60.4%), electric-powered cart (n=11, 22.9%) or unsure of the device type (n=8, 16.7%) had a positive experience. When asked about the reason for choosing the motorized shopping cart (Figure 20), more participants chose the pneumatic-powered cart because it looked new (n=7, 21.9%), they never used it before (n=7, 21.9%) and/or they wanted to try it (n=16, 50.0%). Contrarily, participants chose the electric-powered cart because it was the only one available (n=6, 40.0%) and/or they've used it before (n=7, 46.7%). Table 16 displays additional results about the participants' cart usage characteristics.



	Positive	Neutral	Negative
🟩 Air	29	3	0
🟦 Electric	11	4	0
🟨 Unsure	8	2	0

Figure 19: Participant Experience Results



	It was the only one working.	I've used it before.	It was the only one available.	It looked familiar.	It looked new.	I've never used it before.	I wanted to try it.
🟩 Air	1	4	3	0	7	7	16
🟦 Electric	0	7	6	0	2	1	3
🟨 Unsure	0	0	1	0	3	1	8

Figure 20: Participant Motorized Cart Selection Reasoning

When asked if they would pay to use a motorized shopping cart when visiting the store, most participants responded they would not pay (n=39, 68.4%). However, for those who responded yes, the responses (n=18, 31.6%) were split between $1 (n=6, 30%), $2 (n=7, 35%) and/or $5 (n=7, 35%). As for their total shopping bill, the most common amount spent was between $50-$100 (n=21, 35%).

Table 16: Participant Shopping and Motorized Cart Usage Characteristics

At what location did you most recently use the mobility device?	n	%
Costco	3	5.0
Giant Eagle	50	83.3
Home Depot	1	1.7
Peterson Events Center	1	1.7
Walmart	2	3.3
Other	3	5.0
How many times PER MONTH do you visit this location?		
1-2 times	13	21.7
3-5 times	28	46.7
5-10 times	14	23.3
10-20 times	1	1.7
20+ times	4	6.7
Do you use your personal mobility device or the mobility device available at the store when shopping?		
Personal mobility device	3	5.0
Mobility device available	57	95.0
How often do you use the mobility devices provided at this location?		
Almost never (0% - 25% of the time)	14	24.6
Sometimes (25% - 50% of the time)	15	26.3
Regularly (50% - 75% of the time)	11	19.3
Almost always (75% - 100% of the time)	17	29.8
How often is a mobility device available for you to use when you arrive at the store?		
Almost never (0% - 25% of the time)	6	10.5
Sometimes (25% - 50% of the time)	19	33.3
Regularly (50% - 75% of the time)	19	33.3
Almost always (75% - 100% of the time)	13	22.8
If a mobility device was unavailable, do you know why?		
Battery was dead	14	18.9
Device was broken	3	4.1
All devices were being used	32	43.2
Unsure	20	27.0
Other	5	6.8

Does the availability or quality of the mobility device impact why you shop at this location?		
Yes	34	59.7
No	23	40.3
Where do you place the mobility device when you are finished using it?		
Inside the entrance of the building.	47	72.3
Outside the entrance of the building.	6	9.2
Outside in the parking lot.	6	9.2
Other	6	9.2
How often do you plug in the mobility device to recharge after you are finished using it?		
Almost never (0% - 25% of the time)	7	12.3
Sometimes (25% - 50% of the time)	10	17.5
Regularly (50% - 75% of the time)	17	29.8
Almost always (75% - 100% of the time)	23	40.4

The responses to the open-ended questions provided valuable insight into the need for several improvements and features for both the air and electric-powered carts. Although half of the participants (n=16) who used the pneumatic-powered carts stated no improvements or features were needed, suggestions for improvement were better braking (n=5), higher speed (n=4), bigger basket (n=4), tighter turning radius (n=3), wider/rotating seat (n=2) and longer driving time (n=1). Features suggested for the pneumatic-powered carts were a functional horn (n=4), hook for a cane or purse (n=2), phone holder (n=1) and instructions how to operate and recharge the cart (n=1). Improvements suggested for the electric-powered carts were longer battery life (n=3), higher speed/power (n=2) and bigger basket (n=1) while features requested were a cupholder (n=1) and cell phone charger (n=1). Four participants stated no improvements nor additional features were needed for the electric-powered carts. Participants who were unsure of the type of motorized cart they used responded that improvements were needed to the turning radius (n=1), braking (n=1), speed (n=1) and seat (n=2). Four of the unsure participants stated no improvements nor additional features were needed.

4.3.3 K-Means analysis

The scree plot unsuccessfully provided an obvious "elbow" in the curve but rather ruled out k values larger than five because at six the variance inflation factor dropped below one. As a result, cluster quality was evaluated using the silhouette method for k values of 2, 3, 4 and 5. Cluster quality was highest for three clusters, followed by two clusters and ending equally with four and five clusters. As a result, K-Means clustering analysis and ANOVA tests were performed using two and three clusters. The ANOVA tests using two clusters resulted in the inputs "What is your age?" ($p = 0.007$, $F = 7.926$) and "Do you personally own a mobility device?" ($p < 0.001$, $F = 662.182$) being significant where significance was determined if $p < 0.05$. For 3 clusters, five inputs were significant: "What is your age?" ($p = 0.012$, $F = 4.853$), "Do you personally own a mobility device?" ($p < 0.001$, $F = 325.129$), "How many times per month do you visit this location?" ($p = 0.048$, $F = 3.209$), "What was your total shopping bill for your most recent visit?" ($p = 0.001$, $F = 8.169$) and "How often do you use the mobility devices provided at this location?" ($p = 0.027$, $F = 3.861$). Considering the ANOVA results and cluster sizes, it was determined to use the two cluster K-Means analysis to compare and contrast the two group’s characteristics.

The results of the two cluster analysis yielded 31 individuals in cluster 1 and 26 individuals in cluster 2. The significant differences between the 2 clusters were age and the type of mobility device that they owned. Cluster 1 had a younger overall demographic with 25 individuals versus cluster 2 with 13 individuals being 54 years old or younger. Furthermore, cluster 1 included 27 individuals who stated not owning a mobility device while cluster 2 had 0. Contrarily, cluster 2 included 18 cane or walker users while cluster 1 had 0. Additional differences worth noting between the 2 clusters were the number of individuals who chose to use the pneumatic-powered cart in cluster 1 (n=19) versus cluster 2 (n=13), cluster 1 had more ethnic diversity and cluster 2 individuals were more affluent. Additional detailed results of the cluster analysis can be viewed in Appendix C.

4.3.4 Pneumatic-Powered Cart Usage

Each pneumatic-powered cart needed to be refilled twice a day, once at the beginning of the day and once during the day, during an average 6-hour time period per day of which they were available for use. The refill time ranged from 8-25 minutes depending on the cart. Each cart’s runtime and distance driven were not recorded due to inconsistencies in the operation of the bicycle speedometer.

4.4 Discussion

Incorporating end-user guidance in the design of novel assistive devices is important to maximize the likelihood of meeting actual needs [28, 83, 84]. This pilot study provided insight into the overall usage of motorized shopping carts in a grocery store setting and could be beneficial to grocery stores among other retailers interested in improving their customers' experience. The lack of availability and high demand of the motorized carts observed by the researchers was reinforced by the survey results. Additionally, the study gathered valuable information from users as to what improvements and features could enhance the usability of both types of motorized carts.

The suggested improvements for both types of motorized carts were to be able to drive at higher speeds and have bigger baskets. As for driving at higher speeds, the carts are restricted to a maximum of 0.9 m/s for safety reasons. The size of the basket of the electric-powered carts is 61 cm wide by 61 cm long by 38 cm tall while the basket size of the pneumatic-powered cart is 58 cm wide by 46 cm long and its height tapers from 25 cm tall at the front of the basket down to 12 cm tall towards the rear of the basket. Making the electric-powered cart basket size larger would impact its maneuverability. As for the basket of the pneumatic-powered carts, its size could be increased to that of the electric-powered carts. The suggestion for improvements to the braking of the pneumatic-powered carts needs to be further investigated as participants did not specifically state what needed improvement. Feedback regarding the improvement of the pneumatic-powered carts' turning radius was understandable as it is noticeably larger than the electric-powered carts. The pneumatic-powered carts’ increased turning radius is due to its four-wheel design and longer wheelbase compared to the three-wheel design of the electric-powered carts. However, the four-wheel design makes the pneumatic-powered carts more stable and less likely to tip over.

For participants who stated that they were unaware of the type of motorized cart they used, it is speculated that they most likely used a pneumatic-powered cart due to their reasoning that the cart looked new and/or they wanted to try it. There were some results of the surveys that were unexpected such as one-third of the participants were ages 18-26 and 10 participants stated they used a motorized cart at a location other than the location of the study. However, the latter could be explained based on the possibility that they could have used a motorized cart at a different location due to the screening questions asking if they had used a motorized cart within the past seven days.

The participating site had four electric-powered carts that were consistently in use throughout the day. There were several occasions where site staff were seen pulling the electric-powered carts back to the area where they are commonly charged because of dead batteries. There was one occasion where an electric-powered cart's battery died while the cart was in use in the store. To accommodate the user, a store employee retrieved one of the pneumatic-powered carts for the user to transfer into and use. The employees stated that the electric-powered carts frequently need recharged throughout the day. There was another instance where an electric-powered cart malfunctioned and was deemed no longer usable. As for the pneumatic-powered carts, there were two instances where the carts ran out of air while they were being used. Fortunately, rather than the user exchanging carts and transferring their items, the researcher was able to use a portable, fully charged air tank to partially refill the pneumatic-powered cart to allow the user to finish shopping, thus saving time and preventing further inconvenience.

Overall, it was observed that site employees were not responsible for monitoring the charge level and/or charging of the electric-powered carts. When the electric-powered carts were inoperable due to a dead battery, the employees dealt with it at that time rather than proactively making sure they were charged and/or plugged in when not in use. Many of the users stated in the survey that they plugged in the electric-powered cart to recharge after they were finished using it. However, it was observed that users rarely plugged in the devices after they were finished using them, thus contradicting the survey results. The employees did state that they made sure the electric-powered carts were plugged in to charge overnight. There were numerous instances that both types of motorized carts were not returned to their designated area inside the entrance of the building. It was common for them to be left in the parking lot and/or left at a bus stop close by of which the researchers or store employees retrieved and returned them to their designated area.

A portion of the study was intended for the on-site researcher to step back and allow the site employees to maintain the operation of the pneumatic-powered carts. Unfortunately, the ability to do so didn't occur due to employee scheduling complications and difficulty to find time to train the employees how the pneumatic-powered carts operated and recharged.

The unsuccessful recording of the pneumatic-powered carts runtime and distance driven due to the inaccuracies of the bicycle speedometer are thought to be a result of the low speeds the motorized carts travel versus the higher speeds that bicycles travel. For future studies, the magnetically activated reed switch of the current speedometer will be replaced with a mechanically activated switch of which will be able to accurately record data at the slower speeds. The successful reading of runtime and distance driven will provide a better understanding of how frequently customers use the motorized carts and how well the pneumatic-powered carts perform.

Another unexpected occurrence during the study was the length and inconsistency of time required to recharge the pneumatic-powered carts. Prior to the start of the study, it was expected that the carts could be recharged within a couple of minutes. However, the recharge time was 8 minutes or greater depending on which pneumatic-powered cart was being refilled. It is believed that the flow rate of the storage system is the cause, however the inconsistencies of recharging times between each pneumatic-powered cart needs to be further investigated.

Several limitations of this study deserve discussion. First, because the study included an online survey, individuals without Internet access were unable to complete the survey at their convenience. Although the option for the survey to be completed in person was offered, concerns could be raised for bias effecting the participant’s responses due to being in the presence of the researcher. Second, since the survey was able to be completed online and not in the presence of a researcher, the responses may not be authentic but rather provided by anyone with the link to the online survey. To mitigate this issue in the future, potential participants could be provided with a unique code after they were finished using the motorized cart of which could only be used for a single time. Third, participants were only able to be reimbursed once regardless of how many times they visited the store and used the motorized carts. As a result, they would be unlikely to submit multiple surveys even though they could have had a different experience each time they visited the store. Fourth, the single location of the study and sample size may not have captured the thoughts for the overall population of users. However, the study had to be truncated due to emergency measures taken in response to the COVID-19 pandemic. Fifth, the pneumatic-powered carts were new, and their appearance was very different from that of the electric-powered carts. As a result, the positive results of the survey could have been biased because they may have compared the new appeal of the pneumatic-powered carts to that of the worn electric-powered carts.

4.5 Conclusion

The common unavailability of the electric-powered carts was a concern, most frequently due to their limited number at the store or the battery being dead of which aligned well with their most common requested improvement being a longer battery life. Potential adoption of the pneumatic-powered carts was supported by the positive responses and because many of the individuals wanted to try them even though they never used them before. The improvements and features suggested by participants are priorities to address for future work. Overall, the study results and functional capabilities of the pneumatic-powered carts demonstrated their potential to serve as practical replacements for the current electric-powered carts found in grocery and retail stores.

5.0 Conclusion and Future Work

The research and development performed during this project resulted in the invention of a pneumatic-powered system for PMDs, and ultimately the creation of the PneuScooter and PneuChair. The pneumatic technology's advantages over batteries provide justification for the adoption of the PneuScooter and PneuChair to serve as replacements for battery PMDs. The ability of the pneumatic system to be recharged within minutes for an unlimited number of times is ideal at locations such as retail stores where battery maintenance and monitoring is problematic, often leading to battery PMDs being unusable for long periods of time. Pneumatic PMDs are also able to be stored indefinitely and capable of being quickly deployed in the event of the loss of electricity as a result of a natural disaster. Their waterproof nature renders them superior over battery PMDs in wet environments and opens doors for participation in water related activities such as going to the beach, pool and waterpark. Furthermore, the simple design and lack of electronics results in a safer and more reliable PMD that requires less maintenance and repairs. Although the PneuScooter and PneuChair passed the ISO Wheelchair Standards tests, additional long-term testing should be performed under real-world testing conditions to further evaluate their durability and reliability.

While the numerous advantages of the PneuScooter and PneuChair provide adequate reasoning to serve as feasible replacements for battery PMDs, additional quantitative and qualitative data needs to be collected to expand on the testing performed during this project. The combination of the two data collection approaches is an effective method during product development to understand customer needs and product improvements. For example, qualitative data collection provides insight into user needs and behavior patterns of which are later able to be evaluated for trends. Such trends could then be used to develop survey questions to quantify or place a numerical value on a trend by providing options ranging from “strongly like” to “strongly dislike”, for example. Statistical methods could then be used to determine significance of which would assist with future development. However, the generation of surveys and the results may represent a biased view. The creation of a new survey for a specific study not only requires a clear idea as to what is trying to be understood in terms of a research goal but also the development of questions that are concise, clear and are not biased. One general limitation attributed to the development of a survey by a researcher who is administering the survey as part of their own research could inherently introduce bias due to the design of the questions having preconceived categories and/or favoring the responses towards benefiting their research. A second limitation of surveys is the reliability and validity of the results. Inconsistencies in the data collected could be a result of the variability of participant demographics and study location or simply the lack of consistency or truth in the given responses. One possibility to address this limitation is to ask individuals to complete the same survey at 2 different times resulting in the ability to compare responses for consistency and truthfulness.

Alternatively, quantitative data could be collected first and used to build trends that could later be verified through qualitative data collection. In terms of this project, a more detailed and better understanding of the participants’ responses to the survey could be obtained through follow-up in person interviews and focus groups. As an example, several participants responded to the survey that “better braking” is an area of improvement for the PneuScooter. However, this response raises the question “How could the braking be improved?”, thus a follow-up interview would provide the opportunity to answer such question. Additionally, the successful data collection of the distance driven, time in use and recharging frequency of the devices will allow for the comparison of the effectiveness of using pneumatic technology versus battery technology.

The results of such a comparison could determine whether the pneumatic technology is a better or worse alternative. Although the results of this project are promising and support an argument to bring the PneuScooter and PneuChair closer towards commercialization, additional testing and information is required to effectively drive future product development and business decisions.

Appendix A PneuScooter Optimization Testing

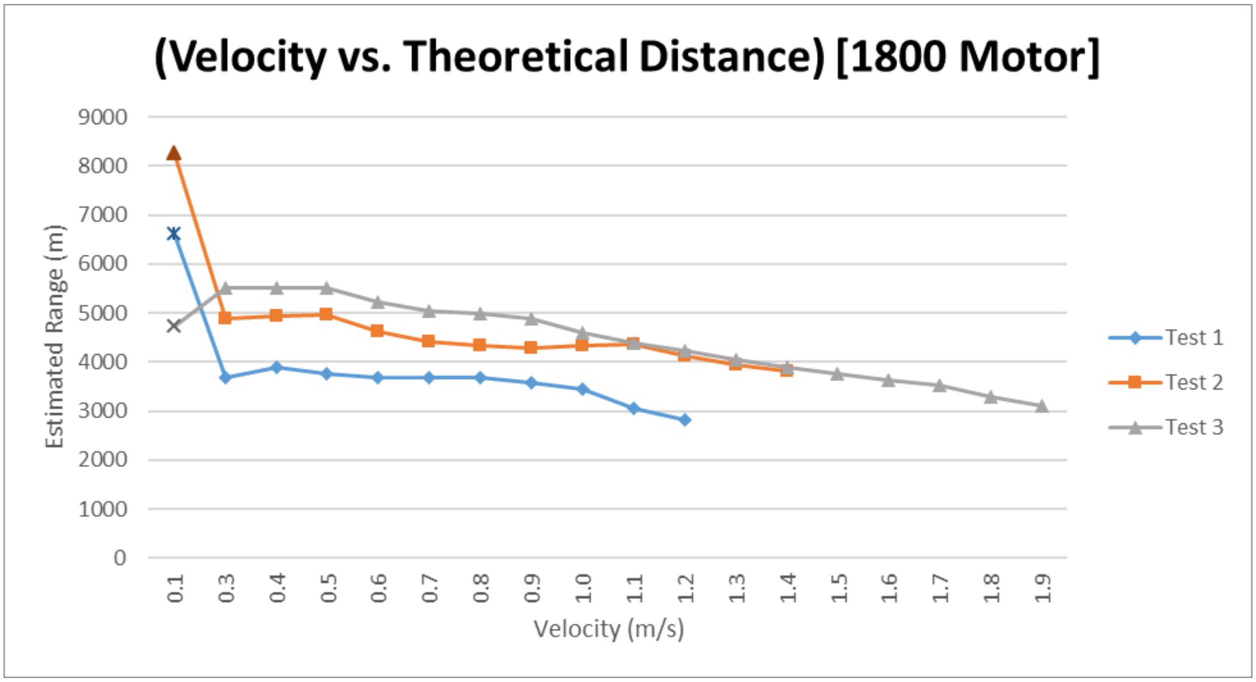


Figure 21: PneuScooter Optimization Testing: Tests 1-3

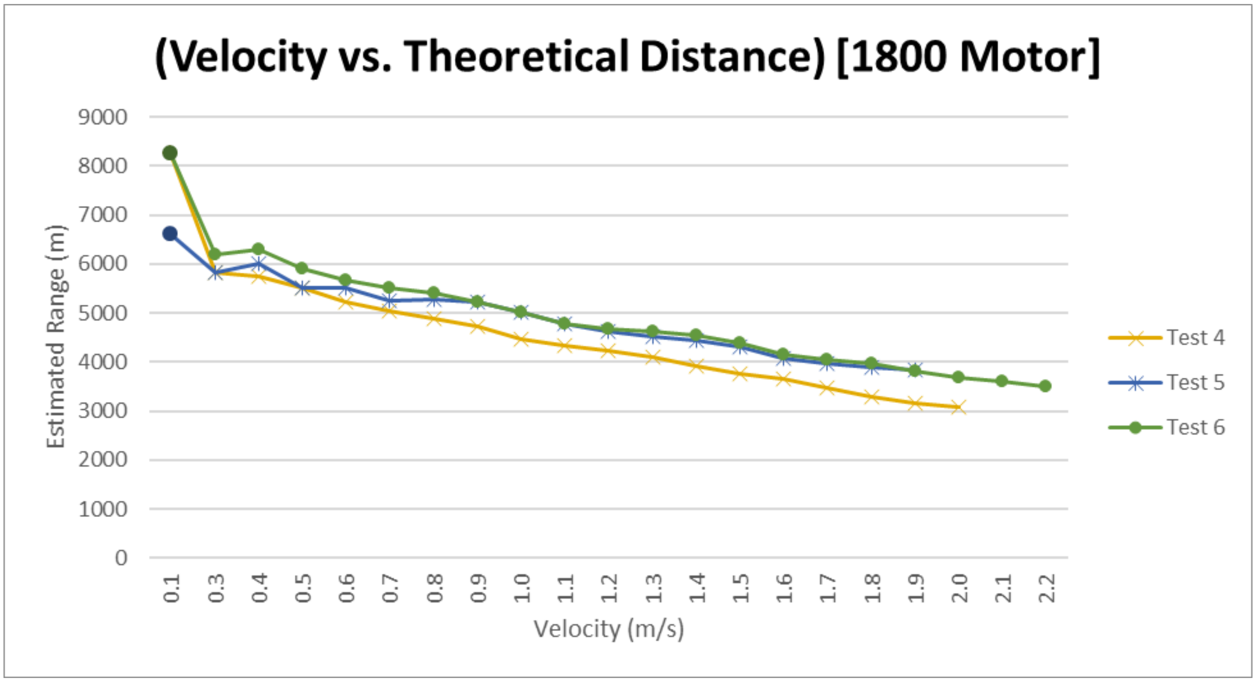


Figure 22: PneuScooter Optimization Testing: Tests 4-6

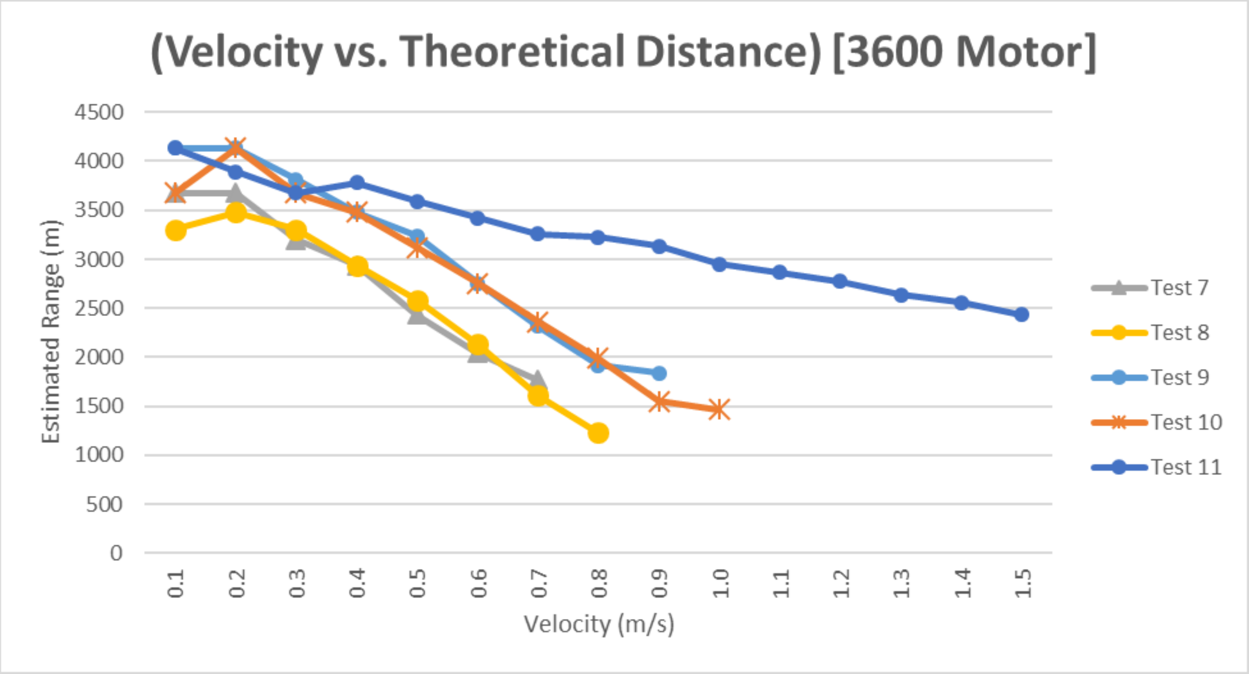


Figure 23: PneuScooter Optimization Testing: Tests 7-11

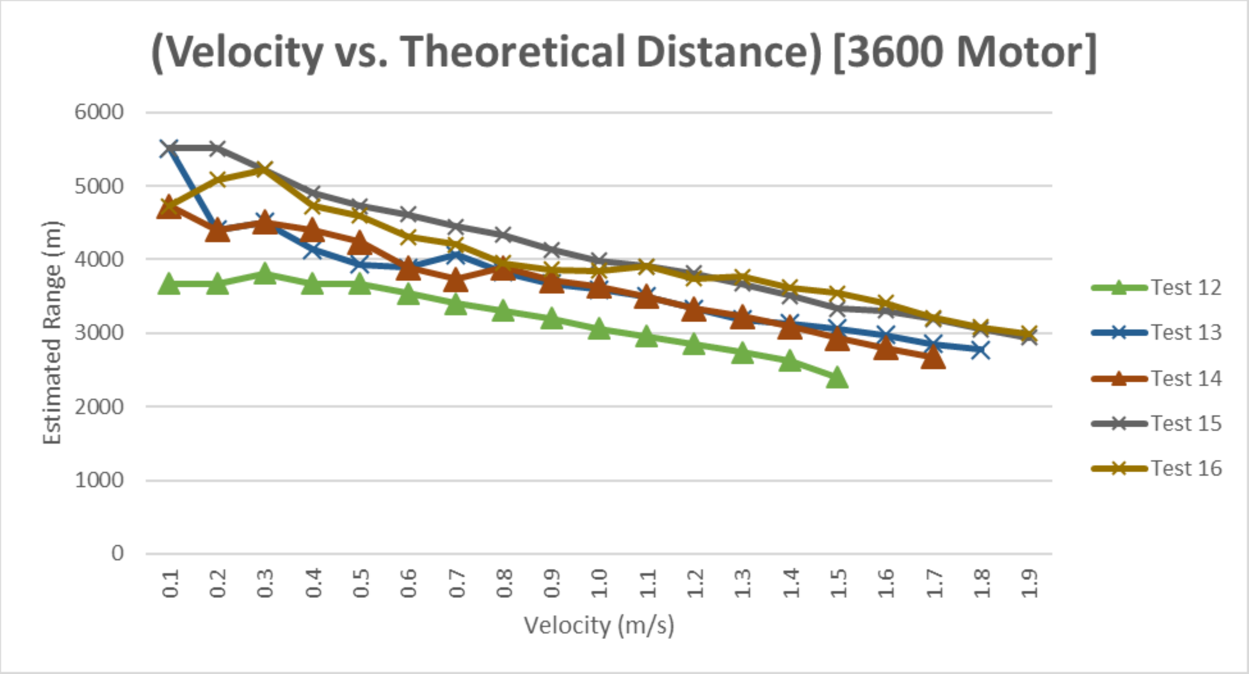


Figure 24: PneuScooter Optimization Testing: Tests 12-16

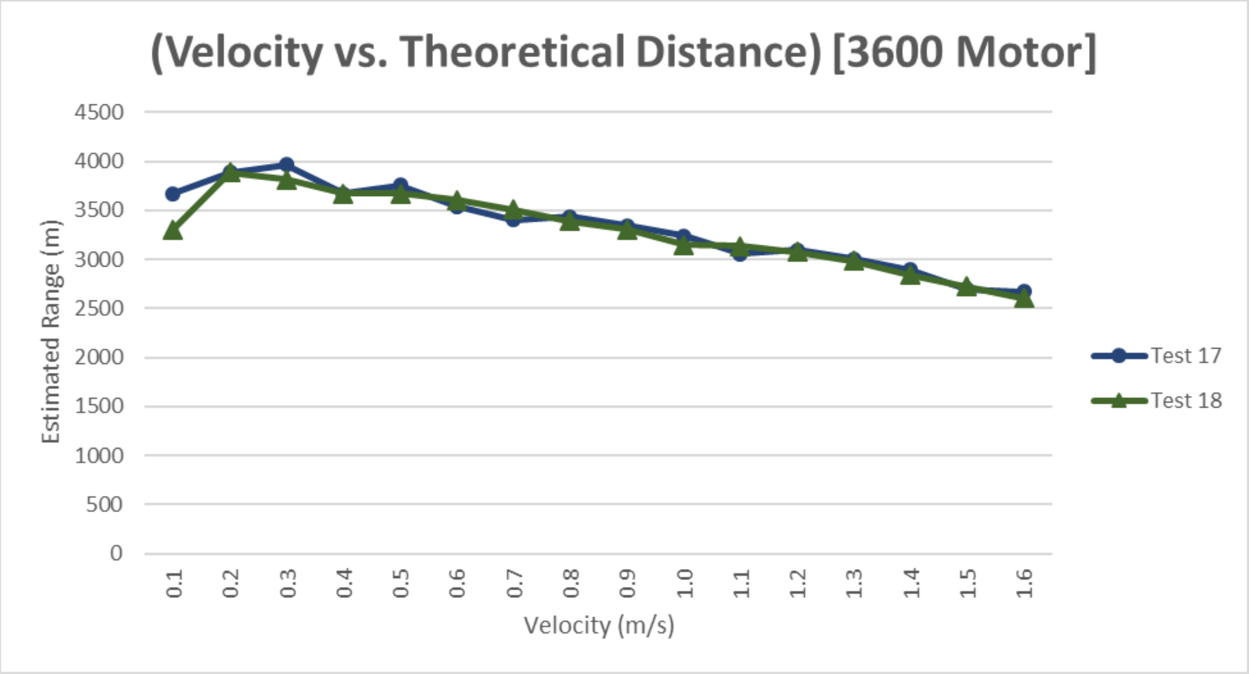


Figure 25: PneuScooter Optimization Testing: Tests 17-18

Appendix B Pilot Study Online Survey

University of Pittsburgh

Powered Mobility Devices in the Community: User Experience Survey

Thank you for your interest in our research study! We are looking at the powered mobility devices used by individuals who use a mobility device when shopping at a big box, grocery store, museum or arena. Our goal through this study is to understand your satisfaction with the functional mobility of the powered mobility device.

You will qualify for this study if:

1) You are 18 years of age or older
2) Have used a loaner powered mobility device within the past 7 days
3) Able to speak and comprehend English

Research Activities

For this study, we will ask you to complete a survey regarding your recent experience using a powered mobility device when shopping.

Participants will be compensated $25 for completion of the survey via an eGift card. You must qualify and complete the entire survey to be compensated.

Data Security

All data collected in this study will be encrypted and securely stored on servers at the University of Pittsburgh. The survey will not access or collect data from your phone, tablet or computer.

Risks and Benefits

There are minimal risks involved in this investigation. Potential risks may include some fatigue with answering the survey questions. This is expected to occur rarely. If it does occur, you will have the option of answering the questions at a later date or takingrest breaks. There is also the risk of breach of confidentiality. The risk for breach of confidentiality will be minimized by allowing only associated research staff access to study information.

There are no direct benefits for your participation in this research study. You may, however, gain the satisfaction of knowing that the knowledge gained in this research could improve the quality of powered mobility devices provided for individuals with disabilities. In addition, the proposed research may benefit all individuals who use powered mobility devices in the future due to changes in health care policy and financial reimbursement for medical services and supplies.

Confidentiality

If you agree to participate, any information about you obtained will be kept as confidential (private) as possible. The collected information will be stored in the University of Pittsburgh's shared drive with restricted access and password protection. Only the Principal Investigator, co-investigators, and associated research staff will have access to your records, along with the individuals described below.

Authorized representatives of the University of Pittsburgh Research Conduct and Compliance Office may review your identifiable research information for the purpose of monitoring the appropriate conduct of this research study. In addition, investigators from the University of Pittsburgh, who are leading this project, may have access to your identifiable research information. Finally, collaborators on this project may have access to coded data for data analysis purposes. Whenever feasible, identifiable data will be removed from the dataset.

Rights of Research Participants Participate

Your participation in this study is completely voluntary and whether you choose to participate or not, will not in any way affect your relationship with the University of Pittsburgh. You may withdraw from this survey at any time with no consequences to you. If you chose to withdraw from the survey, responses made up to that point will be retained. This study is being conducted by Dr. Rory Cooper, PhD. If you have any questions or concerns, please contact one of our clinical coordinators, Nikitha Deepak or Stacy Eckstein at (412) 822-3700.

If you have any questions about your rights as a research subject or wish to talk to

someone other the research team, please call the University of Pittsburgh

Human Subjects Protection Advocate toll-free at 866-212-2668

Conflict of Interest

One or more of the investigators conducting this research has a financial interest in a University of Pittsburgh Licensed Start-up Company called Atimize, Inc. Results of this study may be used for future development of this wheelchair technology, leading to profit for the individual investigator(s) and/or the University of Pittsburgh. Any questions you might have about this will be answered fully by study coordinators Nikitha Deepak or Stacy Eckstein at (412) 822-3700 or by the Human Subject Protection Advocate of the University of Pittsburgh at (866) 212-2668.

Consent

1. We will need to ask you a few screening questions about your eligibility to participate in the study. Do you agree to answer a few screening questions?
   a. I agree to answer the screening questions
   b. I would not like to answer the screening questions

Screening

2. Are you able to comprehend English?
   a. Yes
   b. No

3. Are you 18 years or older?
   a. Yes
   b. No

4. Have you used a loaner powered mobility device at a big box (Walmart, Target, etc.), grocery store (Giant Eagle, Trader Joe's, etc.), museum (Carnegie Science Center, Carnegie Museum of Art, etc.) or arena (Petersen Events Center, PPG Paints Arena, etc.) within the past seven days?
    a. Yes
    b. No

Participate?

5. You are eligible to participate in this survey. If you agree to participate, please click on the "I agree to participate" button below.
    a. I agree to participate
    b. I do not agree to participate

Survey

Thank you for agreeing to participate. The following items are being collected to understand your satisfaction and functional mobility of the powered mobility device.

6. What is your gender?
    a. Female
    b. Male
    c. Prefer not to say

7. What is your ethnicity?
    a. American Indian or Alaska Native
    b. Asian
    c. Black or African American
    d. Native Hawaiian or Other Pacific Islander
    e. White
    f. Other

    g. Prefer not to say

8. What is your age?
    a. Under 18
    b. 18-26
    c. 27-34
    d. 35-54
    e. 55-64
    f. 65 or over
    g. Prefer not to say

9. What is your approximate weight?
    a. Less than 100 pounds (45 kg)
    b. 100-250 pounds (45-110 kg)
    c. 250-400 pounds (110-180 kg)
    d. 400-550 pounds (180-250 kg)
    e. Greater than 550 pounds (250 kg)
    f. Prefer not to say

10. Are you a veteran?
    a. Yes
    b. No
    c. Prefer not to say

11. What year were you born?

____

12. Do you personally own a mobility device?

a. Yes, cane or walker
b. Yes, manual wheelchair
c. Yes, power scooter
d. Yes, power wheelchair
e. No, I do not own a mobility device.

13. At what location did you most recently use the mobility device?

a. Costco
b. Giant Eagle
c. Home Depot
d. Lowes
e. Petersen Events Center
f. Target
g. Trader Joe’s
h. Walmart
i. Whole Foods
j. Other

14. How many times PER MONTH do you visit this location?

a. 1-2 times
b. 3-5 times
c. 5-10 times
d. 10-20 times
e. 20+ times

15. What was your total shopping bill for your MOST RECENT visit?

a. $0-$15
b. $15-$25

    c. $25-$50
    d. $50-$100
    e. $100-$200
    f. More than $200
    g. Prefer not to say

16. Do you use your personal mobility device or the mobility device available at the store when shopping?
    a. I use my personal mobility device.
    b. I use the mobility device available.

17. What was the reason that you chose to use the mobility device? (Select all that apply)
    a. It was the only one working.
    b. It was the only one available.
    c. I've used it before.
    d. It looked familiar.
    e. It looked new.
    f. I've never used it before.
    g. I wanted to try it.

18. What type of mobility device you'd you use during your most recent visit?
    a. Air-powered
    b. Electric-powered
    c. Unsure

19. Please rate your experience using the air-powered mobility device.
    a. Negative
    b. Neutral

c. Positive

20. Please rate your experience using the electric-powered mobility device.
   a. Negative
   b. Neutral
   c. Positive

21. Please rate your experience using the mobility device.
   a. Negative
   b. Neutral
   c. Positive

22. Why was it a negative experience? What could be improved?

____

23. Why was it a neutral experience? What could be improved?

____

24. Why was it a negative experience? Could anything be improved?

____

25. How often do you use the mobility devices provided at this location?
   a. Almost never (0%-25% of the time)
   b. Sometimes (25%-50% of the time
   c. Regularly (50%-75% of the time)
   d. Almost always (75%-100% of the time)

26. How often is a mobility device available for you to use when you arrive at the store?
   a. Almost never (0%-25% of the time)

b. Sometimes (25%-50% of the time
c. Regularly (50%-75% of the time)
d. Almost always (75%-100% of the time)

27. If a mobility device was unavailable, do you know why? (Select all that apply)
    a. Battery was dead
    b. Device was broken
    c. All devices were being used
    d. Unsure
    e. Other

28. Does the availability or quality of the mobility device impact why you shop at this location?
    a. Yes
    b. No

29. Where do you place the mobility device when you are finished using it? (Select all that apply)
    a. Inside the entrance of the building.
    b. Outside the entrance of the building.
    c. Outside in the parking lot.
    d. Other

30. How often do you plug in the mobility device to recharge after you are finished using it?
    a. Almost never (0%-25% of the time)
    b. Sometimes (25%-50% of the time
    c. Regularly (50%-75% of the time)
    d. Almost always (75%-100% of the time)

31. If required, would you pay to use a mobility device provided by this location?

    a. Yes
    b. No

32. How much would you pay to use the mobility device? (Select all that apply)

    a. $1
    b. $2
    c. $5
    d. $10
    e. $15
    f. $20
    g. $25

33. Are there any features that would make the mobility device more useful for you?

    ____

Appendix C K-Means Analysis Results

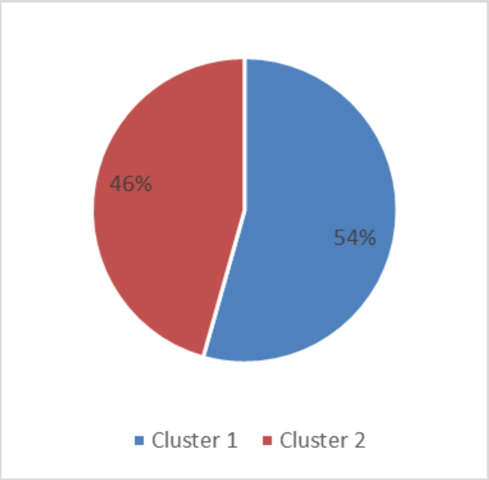
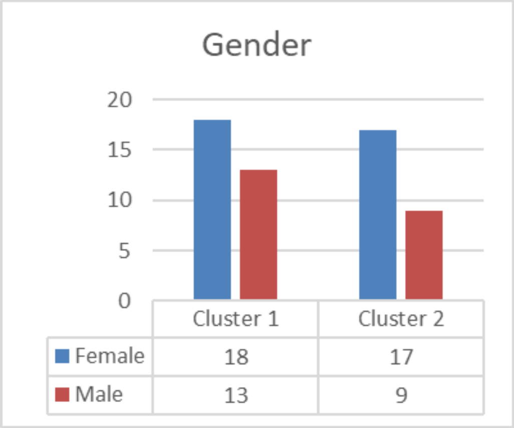
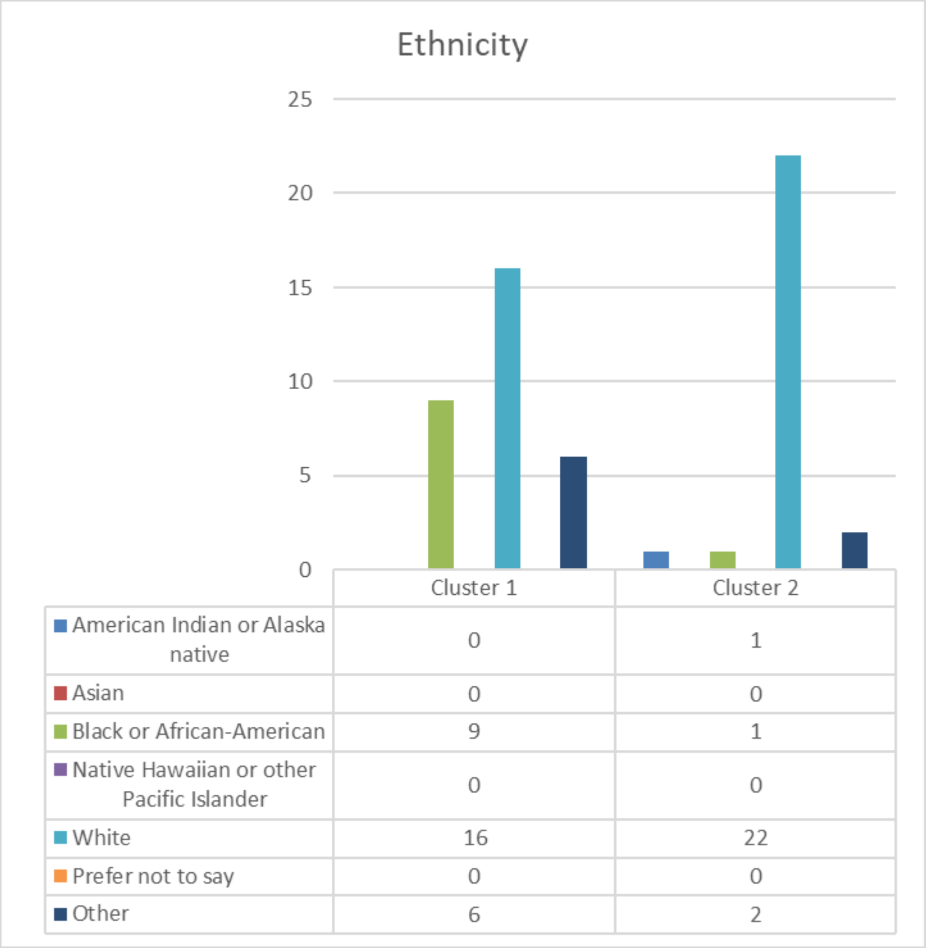


Figure 26: K-Means Clustering – Cluster Size



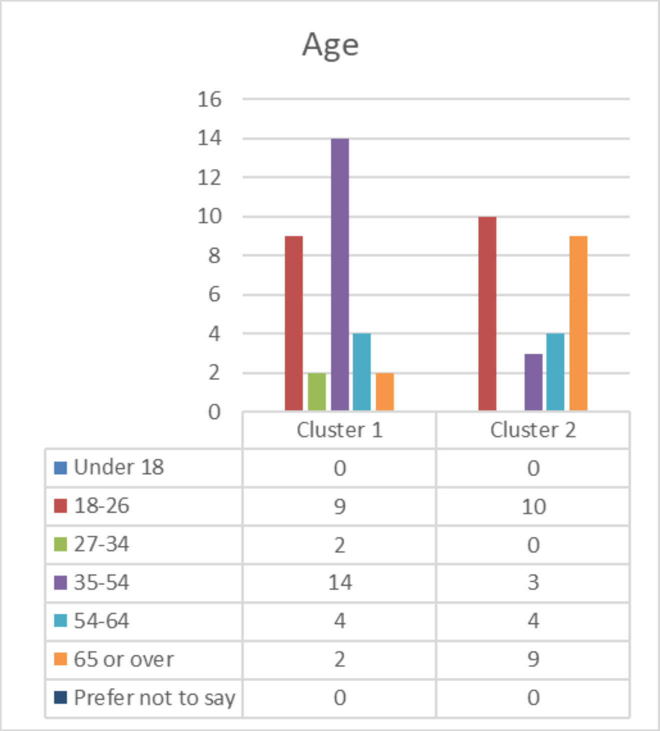
	Cluster 1	Cluster 2
🟦 Female	18	17
🟥 Male	13	9

Figure 27: K-Means Clustering – Gender



	Cluster 1	Cluster 2
🟦 American Indian or Alaska native	0	1
🟥 Asian	0	0
🟩 Black or African-American	9	1
🟪 Native Hawaiian or other Pacific Islander	0	0
🟦 White	16	22
🟧 Prefer not to say	0	0
🟦 Other	6	2

Figure 28: K-Means Clustering – Ethnicity

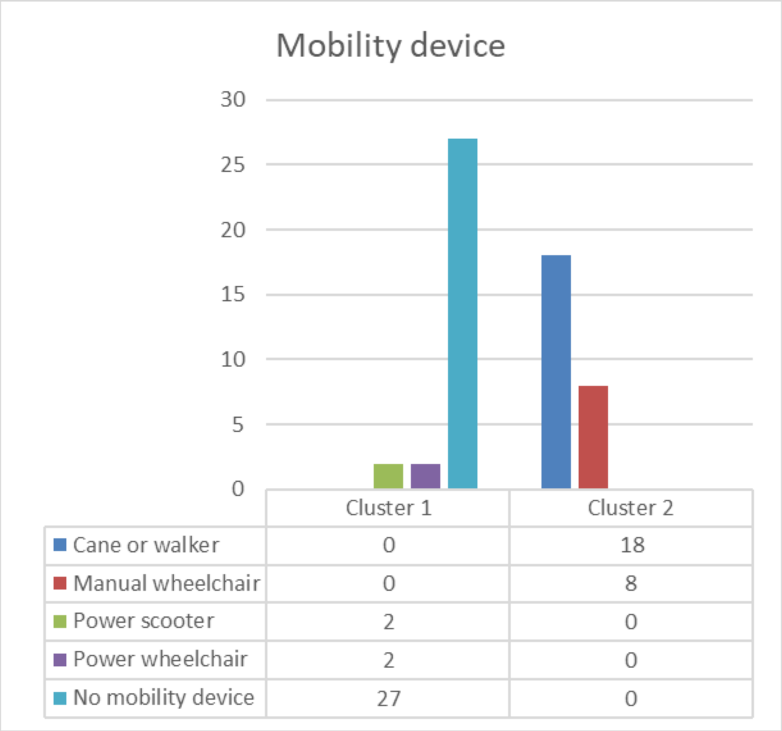


	Cluster 1	Cluster 2
🟦 Under 18	0	0
🟥 18-26	9	10
🟩 27-34	2	0
🟪 35-54	14	3
🟦 54-64	4	4
🟧 65 or over	2	9
🟦 Prefer not to say	0	0

Figure 29: K-Means Clustering – Age

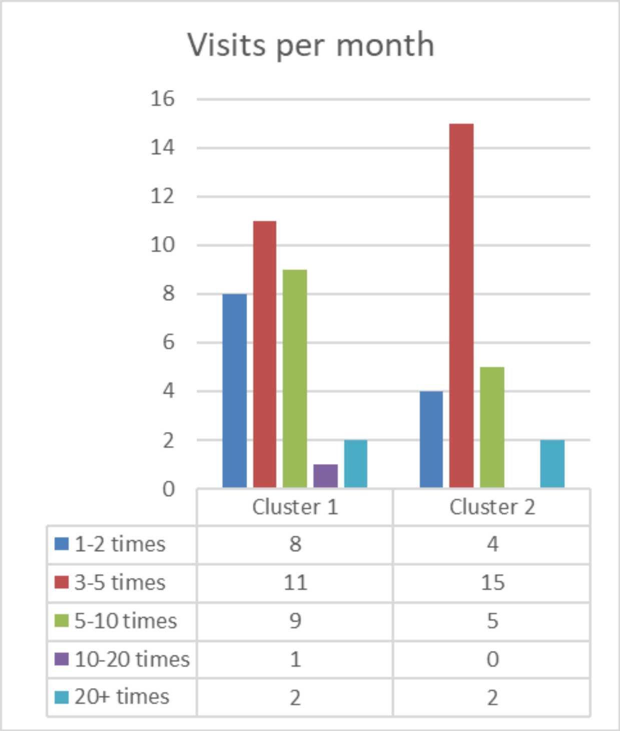
	Cluster 1	Cluster 2
🟦 Less than 100 pounds	0	0
🟥 100-250 pounds	21	18
🟩 250-400 pounds	10	8
🟪 400-500 pounds	0	0
🟦 Greater than 500 pounds	0	0
🟧 Prefer not to say	0	0

Figure 30: K-Means Clustering – Weight



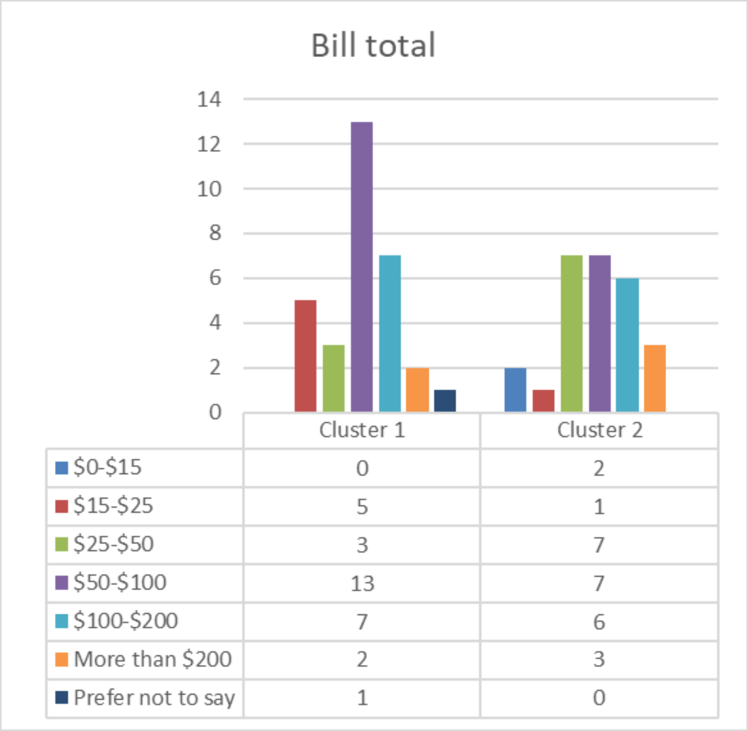
	Cluster 1	Cluster 2
Cane or walker	0	18
Manual wheelchair	0	8
Power scooter	2	0
Power wheelchair	2	0
No mobility device	27	0

Figure 31: K-Means Clustering – Mobility Device



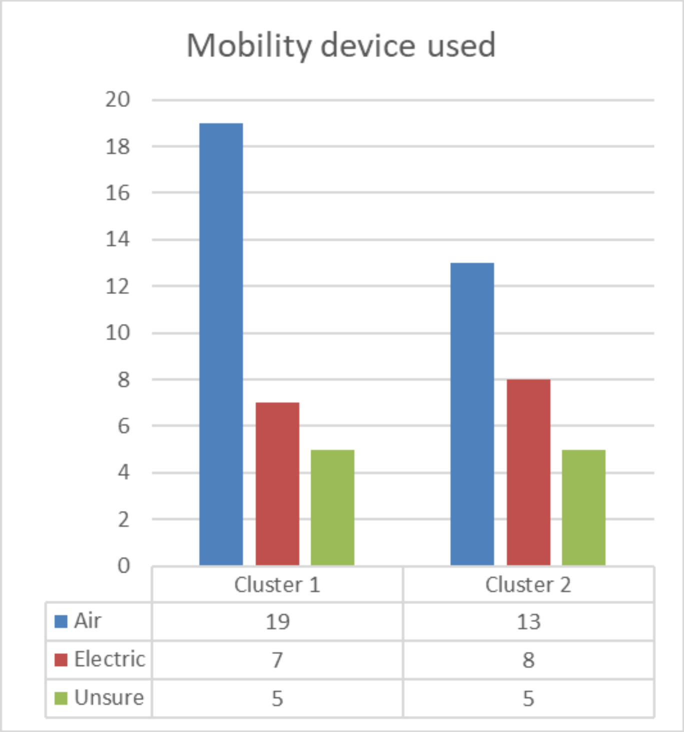
	Cluster 1	Cluster 2
1-2 times	8	4
3-5 times	11	15
5-10 times	9	5
10-20 times	1	0
20+ times	2	2

Figure 32: K-Means Clustering – Visits per Month



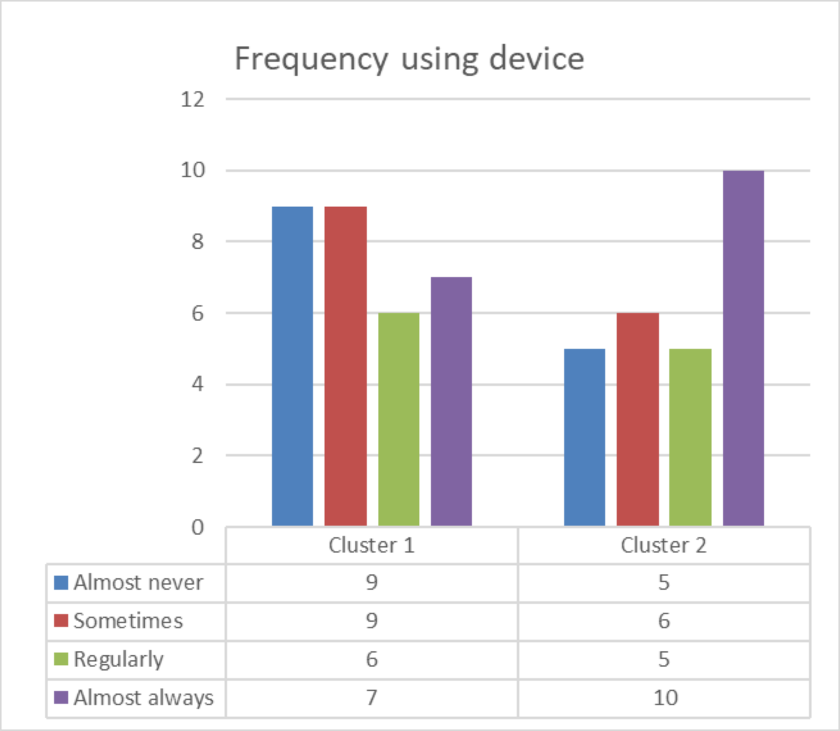
	Cluster 1	Cluster 2
🟦 $0-$15	0	2
🟥 $15-$25	5	1
🟩 $25-$50	3	7
🟪 $50-$100	13	7
🟦 $100-$200	7	6
🟧 More than $200	2	3
■ Prefer not to say	1	0

Figure 33: K-Means Clustering – Bill Total



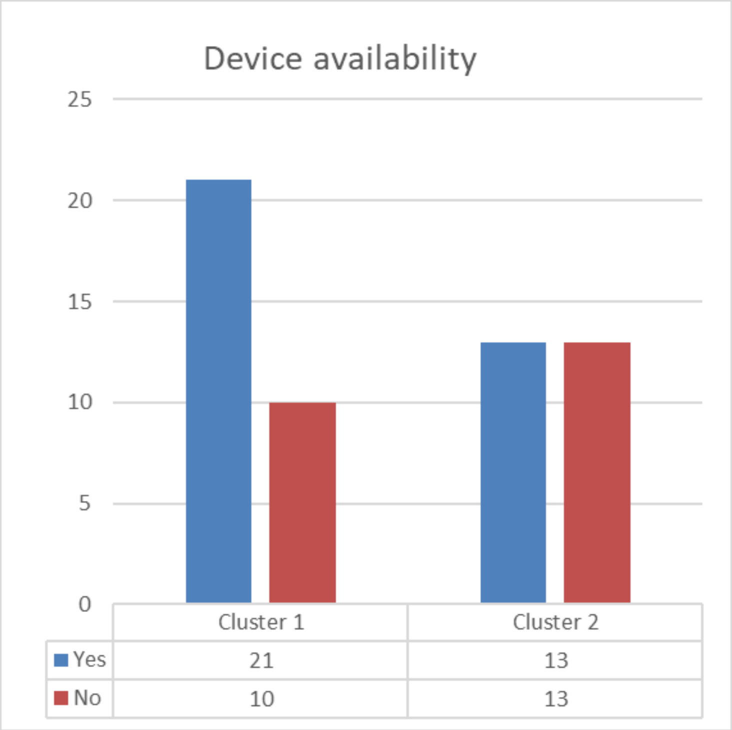
	Cluster 1	Cluster 2
🟦 Air	19	13
🟥 Electric	7	8
🟩 Unsure	5	5

Figure 34: K-Means Clustering – Mobility Device Used



	Cluster 1	Cluster 2
🟦 Almost never	9	5
🟥 Sometimes	9	6
🟩 Regularly	6	5
🟪 Almost always	7	10

Figure 35: K-Means Clustering – Frequency Using Device



	Cluster 1	Cluster 2
🟦 Yes	21	13
🟥 No	10	13

Figure 36: K-Means Clustering – Device Availability

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