# Metabolic Cost of Overground Walking Using a Motorized Walker-like Exoskeleton

UNDERGRADUATE THESIS

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By

Jasper Hu

Undergraduate Program in Aerospace Engineering

The Ohio State University

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Thesis Committee

Dr. Manoj Srinivasan, Advisor

Dr. Sandra Metzler

**Abstract**

Those with movement disorders commonly use exoskeletons and assistive walking devices. The purpose of most exoskeletons and assistive walking devices is to reduce the effort required to perform a task by providing mechanical assistance to the user. A way to measure effort is by studying metabolic cost. Thus, by providing mechanical assistance when performing a task, the metabolic cost of performing the task may decrease. Previous studies showed a passive walker-like exoskeleton cart in some configurations decreased the metabolic cost of walking [1]. Since such findings, a brushless DC motor was added to the cart to provide an adjustable assistive forward force on the user while walking. This research aims to determine the relationship between the intensity of the assistive forward force, metabolic cost, and walking speed when overground walking with the cart. To do so, metabolic and walking speed data was collected from five subjects using a COSMED K5 system and a video camera respectively. Each subject completed ten six-minute trials where nine of the trials were used to collect walking data. The trial order was randomized. One of the trials was used to collect normal walking data in which the subjects walked normally, without the cart. The metabolic cost and walking speed from this normal walking trial were used as the baseline metabolic cost and walking speed during data analysis.

When averaging across the five subjects, the cart was shown to decrease walking speed for all but the greatest assistance level (potentiometer setting 4.2, corresponding to large assistance). The cart increased the average metabolic cost per unit time from normal walking for all assistance levels except one (potentiometer setting 3.6, corresponding to medium assistance) and increased the average metabolic cost per unit distance from normal walking for all

assistance levels. However, analyzing the data subject-wise, we found that the cart decreased metabolic rate below normal walking for four out of the five subjects and that the cart decreased the metabolic cost per unit distance for three out of the five subjects (with one subject showing a marginal increase). These decreases suggest that the cart may be promising. Further research will be required to determine how the cart can be modified or how much training the subjects need to be provided such that the cart becomes a more uniformly assistive walking device. Should the cart be modified and proven to reduce the metabolic cost of walking, the cart may replace other devices and provide a framework for future device designs.

**Acknowledgements**

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# Chapter 1. Introduction

## 1.1 Background and Motivation

Currently, many exoskeletons and assistive walking devices are being used in both day-to-day applications and rehabilitation settings. Such exoskeletons and assistive walking devices vary drastically in complexity level. For example, canes, crutches, and four-footed walkers are relatively simple assistive walking devices, while the Lokomat and Indego are examples of relatively complex devices (Figures 1 and 2). Here, complexity is characterized by the number of moving parts and the presence of electronics and control structures. Due to the complexity of some of the devices, the devices may be difficult to model, which may result in a lack of knowledge regarding how the users and devices interact [1]. Regardless of the complexity or type of device, the overarching goal of such devices is to reduce the effort required to perform a task by providing mechanical assistance to the user. A simple way to quantify the effort required to perform a task is to analyze the metabolic cost, which measures how much metabolic energy is required to perform the task. Thus, if the purpose of exoskeletons and assistive walking devices is to decrease the effort needed to perform a task, then determining whether the devices increase, incur no change, or decrease the metabolic cost of performing the task is one way to quantify the effectiveness of such devices. Zimmerman set out to design and test a mechanically simple, and therefore easy to model, walker-like exoskeleton in hopes of reducing the metabolic cost of walking [1]. Zimmerman's work will be outlined in greater detail in section 1.3 (Previous Work). This research will examine the metabolic benefit of a modified version of the exoskeleton developed by Zimmerman.


Figure 1. Image of the Lokomat robotic rehabilitation device. The Lokomat is a powered and stationary exoskeleton used in rehabilitation settings. The image highlights the level of complexity of the equipment. The Lokomat represents what is referred to throughout the paper as a complex assistive walking device [2].

Figure 2. Image of the Indego exoskeleton. The Indego is a powered exoskeleton that has many moving parts and is highly adjustable. The Indego represents what is referred to throughout this paper as a complex assistive walking device [3].

### 1.2 Literature Review

Some examples of exoskeletons and assistive walking devices include the Lokomat, Indego, LifeWalker, four-footed walkers, and rollators [4], [5]. While some of the listed devices, such as the Lokomat and Indego, may help those with movement impairments walk, they may also be incredibly complex and challenging to model. For example, a hip exoskeleton developed by Seo, Lee J., Lee Y., Ha, and Shim [6] relied on a complex control structure that changed the behavior of the exoskeleton based on the user. Though the device was complex, the device was shown to decrease the net metabolic rate per unit body weight of walking by approximately 13.2% [6]. The device is shown below in Figure 3.


Figure 3. Image of the exoskeleton developed by the Samsung Advanced Institute of Technology. The exoskeleton reduced subjects' net metabolic rate per unit body weight while walking. The device contained complex components like a brushless DC motor, a joint actuator, a spring-loaded sliding mechanism, a CPU, and a battery. Additionally, the device was controlled using a complex control structure [6].

However, many simpler assistive walking devices are currently used in various applications. Unfortunately, many of these devices increase the metabolic cost of walking. Traditionally, simple, non-motorized walkers have been prescribed to people who suffer from movement disorders that prevent them from walking independently. Some examples of such walkers are simple, two-wheeled, four-wheeled, and four-footed walkers. An image of a four-wheeled walker may be seen in Figure 4. These walkers can be simple and relatively affordable given the typical lack of electrical components. Due to their simplicity, such walkers also make studying the interactions between the humans and the walkers simpler. However, Priebe and Kram [7] have shown that two-wheeled, four-wheeled, and four-footed walkers increase the metabolic cost per unit distance of walking by 17%, 4%, and 82% respectively when walking at a speed of 0.3 m $s^{-1}$. Priebe and Kram studied the effects of the four-footed walker by having subjects stand still and repeatedly pick up the walker at a similar cadence to that seen when walking with the walker. Subjects also walked, without any assistance or walker, at the same cadence seen when walking with the four-footed walker. The sum of the metabolic cost of these two actions was very similar to the metabolic cost of walking with the four-footed walker. Thus, the significant increase in metabolic cost per unit distance may have been because the four-footed walker altered the typical gait pattern of the user and required the user to pick up the walker each step [7].

Figure 4. Example of a typical four-wheeled walker. The typical four-wheeled walker is an example of a simple assistive walking device [8].

Jayaraman *et al* [5] also showed that the metabolic cost of walking changed with the type of assistive walking device. For example, it was shown that the LifeWalker, which is a four-wheeled walker designed such that the user rests their forearms on the walker instead of only relying on their hands, resulted in a lower metabolic cost of walking compared to standard rollators and predicate devices [5]. An image of the LifeWalker may be seen in Figure 5. Overall, these two studies demonstrated the pitfalls of some commonly used assistive walking devices by proving that many of these devices increase the metabolic cost of walking. Thus, the two previous studies highlighted the need for new simplistic assistive walking devices that minimally alter or decrease the metabolic cost of walking.


Figure 5. Image of the LifeWalker. The LifeWalker is an example of a simple assistive walking device. Unlike traditional four-wheeled walkers, the LifeWalker supports users by their arms instead of their hands [9].

Many people like Collins, Wiggin, and Sawicki [10] have begun designing simple and easy-to-model exoskeletons to address some of the pitfalls of current assistive walking devices. The three developed a simple exoskeleton to aid the calf muscle while walking (Figure 6). This study showed that the exoskeleton reduced the metabolic cost of walking by approximately 7.2% when a 180 N m $rad^{-1}$ spring was used in the exoskeleton. Because the exoskeleton was simple and isolated to a small portion of the human body, it was easier to understand how the exoskeleton interacted with the human body [10]. This study proved that simple devices that are easy to model can reduce the metabolic cost of walking.

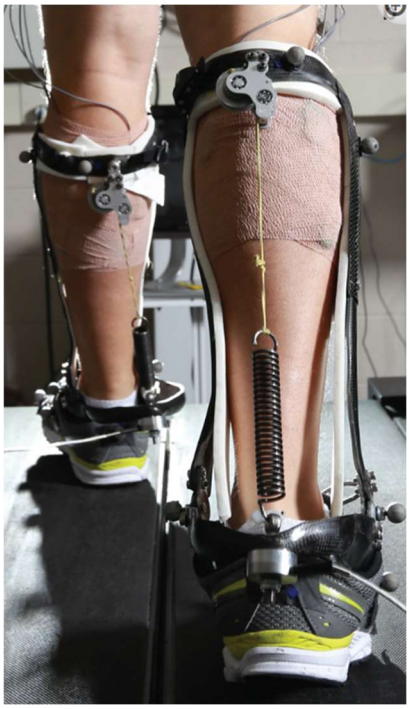

Figure 6. Image of an exoskeleton developed to aid the calf muscle while walking. Though the device was more complex than a walker, the device was still relatively simple due to the lack of electronics and control structures. The device was shown by the developers to be easy to model [10].

**1.3 Previous Work**

Zimmerman [1] developed a walker-like cart in the Movement Lab at The Ohio State University. Zimmerman intended for the cart to be mechanically simple, easy to model, strong enough to support the user, easily maneuverable, easily utilized by users of various sizes, powerful, safe, and throttleable. The final cart design was mechanically simple and consisted of a metal frame with four caster wheels where users would attach themselves to the inside of the cart via a gait belt and springs. An image of the passive version of the cart is shown below in Figure 7.

Figure 7. Passive version of the cart. In the image are the frame, caster wheels, and springs used to build the passive version of the cart. The general frame geometry, caster wheels, and spring locations remained mostly unchanged for the motorized version of the cart [1].

Zimmerman recorded and analyzed metabolic data for treadmill walking at 1.2 m $s^{-1}$ for two configurations of the cart. The first was the untied configuration where the cart and subject were free to move on the treadmill in all directions. The second was the tied configuration where the cart was tied to the front of the treadmill, thus simulating an active cart with a motor to provide a propulsive force. In each configuration, Zimmerman varied the spring stiffness of the springs that attached the user to the cart from 0-750 N $m^{-1}$. Overall, Zimmerman's results showed that the untied configuration of the cart increased the metabolic cost of walking while the tied configuration resulted in a mean percent reduction of 7.5% in the metabolic cost of walking for spring stiffnesses of 221-732 N $m^{-1}$. Additionally, it was shown that walking with the tied cart, even with zero spring stiffness, resulted in a mean percent reduction of 5.2% in metabolic cost. Lastly, due to the mechanical simplicity of the cart, Zimmerman utilized previously developed walking models and metabolic data collected during the treadmill walking

experiments to formulate a mathematical model for the metabolic cost of walking with the cart. The model showed that metabolic rate decreased as spring stiffness increased [1].

Riemerschmid, Kini, and Mattar continued Zimmerman's work by analyzing Zimmerman's data and testing a motorized version of the cart [11], [12], [13]. Initially, a brushless DC motor was installed, and a hall effect sensor was used for the throttle to provide set levels of assistance. With this configuration, Kini showed that the cart increased the user's overground walking speed if the user's typical walking speed was less than the speed associated with the provided assistance level. Subsequently, Kini showed the inverse was also true where the user's overground walking speed decreased if the assistance level corresponded to a speed slower than the user's typical walking speed. However, Kini's main finding was that a propulsive force of 0-16.8 N was the optimal assistance level range for reducing metabolic rate while walking [12]. Building on Kini's work, Mattar replaced the hall effect sensor with a precision potentiometer so that more motor speeds could be tested with greater consistency and reliability. Mattar discovered similar trends to Kini in that as the assistance level increased, the user's overground walking speed also increased. Additionally, Mattar showed that with no assistive propulsive force, the cart tended to decrease each subject's overground walking speed by approximately 0.2 m $s^{-1}$, likely because the user needed to drag the cart along [13].

Overall, though overground walking speed tests have been performed, overground walking metabolic data had yet to be collected. All overground metabolic analyses for the powered version of the cart relied on Zimmerman's mathematical model that was developed and validated using treadmill walking data for the unpowered version of the cart. Therefore, this research focused on collecting overground walking metabolic data that could be compared to

the previously collected treadmill walking metabolic data. Such data helped determine whether the cart was an effective assistive walking device for overground walking. Additionally, because this research utilized the motorized version of the cart, the results provided insight into the accuracy of Zimmerman's tied configuration that approximated the motorized version of the cart.

### 1.4 Research Goals

We had the following three goals:

1. to upgrade the cart to improve the human-machine interaction without significantly altering gait mechanics or increasing the complexity of the cart,
2. to quantify the effect of the cart and its various propulsive assistance levels on the metabolic cost of overground walking, and
3. to quantify the effect of the cart and its various propulsive assistance levels on overground walking speed.

## Chapter 2. Methods

### 2.1 Cart Modifications

Before performing the experiments outlined below in section 2.5 (Overground Walking Trials), the cart was tested, and a pilot study was performed. While testing the cart, multiple pitfalls of the cart were highlighted and fixed. The first issue detected during testing was the amount of slack in the old springs. The old springs had stretched over time and no longer firmly attached the cart to the subject. To ensure the springs securely adhered the cart to the subject, shorter springs were purchased and installed. The new springs, described in Table 5 in the Appendix, were five inches long and had an outer diameter of 0.5 inches. A comparison in length between the old and new springs in each direction may be seen below in Figure 8.

Figure 8. Comparison between the old and new springs. On the far right is one of the new springs. On the left are the four old springs. Going from left to right, the first two were the springs used along the frontal plane. These springs were shorter than the rest because of how close the left and right hips of subjects were to the cart frame. The middle-right spring attached the front of the subject to the front of the cart. Lastly, the rightmost spring, which was also the longest spring, attached the posterior side of the subject to the rear of the cart.

The chosen springs had a similar spring constant and length to the original springs shown to decrease the metabolic rate per unit mass in Zimmerman's experiments [1]. These springs that resulted in minimum metabolic rate during Zimmerman's experiments were also used in the following work performed by Kini and Mattar that was outlined in section 1.3 (Previous Work) [12], [13].

The second issue detected during testing was the subject's location inside the cart. Originally, the maximum assistance level in the experimental protocol corresponded to a potentiometer setting of 4.6. At assistance levels this great, subjects would be encouraged to walk much quicker than typical walking speeds and would subsequently lean more in the aft direction to compensate for the high propulsive force. Thus, throughout testing, there were multiple instances in which the user contacted the wires or rod holding the motor on the back of the cart with the heels of their feet while being subjected to high levels of propulsive force. The location and configuration of the wires and rod are shown in Figure 9 below.

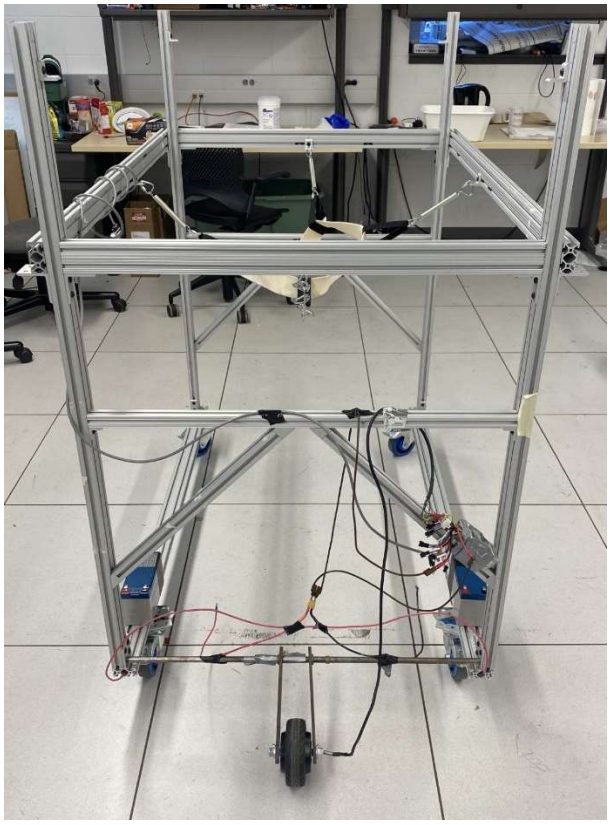

Figure 9. Location and configuration of the brushless DC motor, the rod holding the motor, and the wires. This picture was taken from the rear of the cart.

Subjects contacting components on the back of the cart was troublesome for multiple reasons. Doing so could cause the subject to trip, which would increase the risk of injury during the experiment. Additionally, the wires on the back of the cart connected the two batteries to the motor controller, which subsequently provided power to the motor. Contacting the wires could detach the wires from the batteries, which would result in the motor powering off and providing no assistance. If such an event occurred during a trial, the trial would need to be excluded and reperformed. In addition to securely attaching subjects to the cart, shorter springs also reduced the risk of subjects contacting the wires and rear rod with their heels at high assistance levels by biasing subjects towards the front of the cart where no electronics

were. Figures 10 and 11 below demonstrate how the subject was biased forward using the shorter springs.

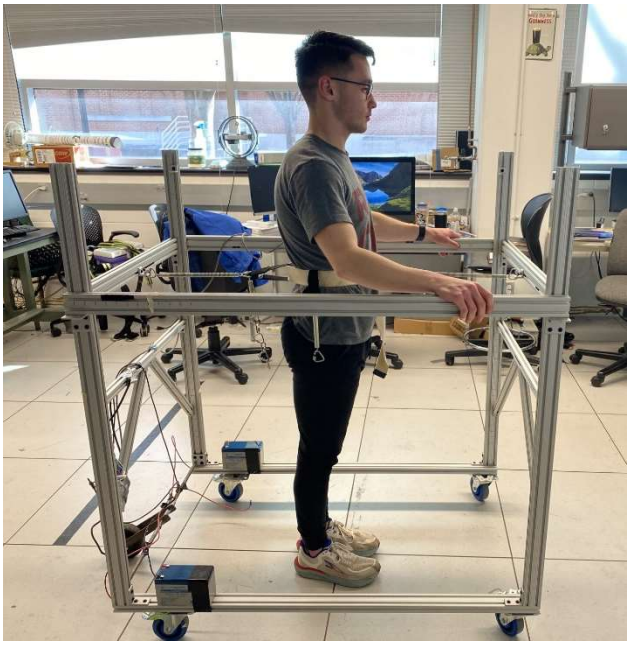

Figure 10. Location of the subject with the old springs installed. With the old springs installed, the subject was located towards the center of the cart.

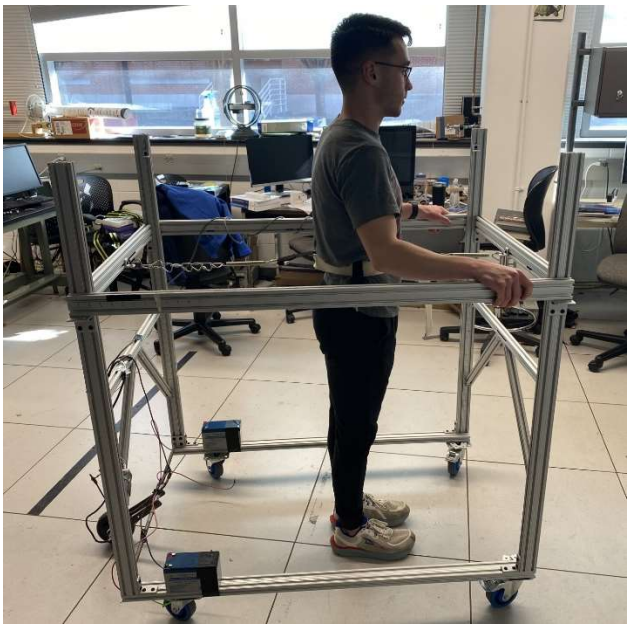

Figure 11. Location of the subject with the new springs installed. With the new springs installed, the subject was biased forward with respect to the cart. Connecting links were attached in series to the rear spring to increase the distance of the subject from the rear of the cart.

Because the new springs were shorter, triangle-shaped connecting links were connected in series to make up for the missing length of the rear spring. The connecting links were expected to act as a rigid body throughout the experiment, and therefore should not have significantly altered the performance of the rear spring while walking with the cart. The use of the connecting links in combination with the rear spring may be seen in Figure 11.

The final issue during testing was the motor not remaining powered on at low assistance levels. The lowest assistance level used during testing in which the motor was powered on corresponded to a potentiometer setting of 3.2. This setting was close to the lowest operational setting of the potentiometer (3.0). 3.0 was the lowest operational setting of the potentiometer because this setting corresponded to a 1.7 V input to the motor controller, which was the minimum required for the motor to run [13]. At a potentiometer setting of 3.2, the motor would sometimes shut down while being wound up if the subject and cart were not already

moving. Additionally, the setting was so low that it could be difficult for the subject to determine whether the motor remained powered on throughout the trial. Thus, to erase such ambiguity and to ensure the collected metabolic and walking speed data corresponded to the correct motor assistance level, the minimum potentiometer setting used throughout the experiment was changed to 3.3. More information regarding the potentiometer settings used throughout the experiment can be found in section 2.5 (Overground Walking Trials).

**2.2 Human Subject Population**

The human subject population consisted of 5 healthy adults with 1 female and 4 male subjects. The average age, height, and mass of the subjects were 23 years, 175.2 cm, and 68.5 kg respectively. Subjects had no movement disorders.

**2.3 Walking Speed Data Collection**

Walking speed data was collected via video recording. A camera was located towards the end of one of the two long straightaways of the chosen path. The camera was directed such that the side profile of the subject walking was recorded. Additionally, the camera was placed as far back from the walking path as possible to maximize each subject's time in the camera's field of view. To calculate average walking speed, a reference length was used (approximately 2.76 m). This distance was chosen because it was the maximum distance viewable from the camera's field of view across all subjects. Thus, the distance between two points on the wall in the frame of the camera was measured. The timestamps in which the front plane of the cart closely aligned with each of the two points were recorded. During the no cart trial, the front cap on the COSMED K5 mask was used instead of the front of the cart to determine when subjects closely

aligned with the reference points. Because each trial was six minutes long and the path was a closed loop, subjects passed the camera multiple times. Thus, timestamps for each point were recorded every time subjects came around. For each lap, the difference between the two timestamps was calculated in terms of seconds. The differences within a trial were averaged across the number of laps in which timestamps were recorded. The distance between the two points was then divided by the average time spent between the two points to find subjects' average speed for a given trial ($\text{Speed} = \frac{\text{Distance}}{\text{Time}}$).

**2.4 Metabolic Cost Data Collection**

Metabolic data was collected throughout experiments to establish a relationship between assistive propulsive force, energy expenditure, and walking speed. A COSMED K5 wearable metabolic system was used to collect metabolic data. COSMED K5 is a portable respiration-based metabolic system that records the volumetric flow rates (mL $min^{-1}$) of oxygen and carbon dioxide in subjects' respiration. Due to the portable nature of the COSMED K5 system, subjects could walk with the device independent of any additional computational devices, like a computer.

Each trial was six minutes long. The first four minutes of each trial were used to get the subject into a metabolic steady state, while the remaining two minutes were used to collect steady state metabolic data. Thus, though metabolic data was collected for the entirety of each six-minute trial, the metabolic data from the first four minutes of each trial was discarded, and only the data from the final two minutes was analyzed. The steady state data obtained in the final two minutes of each trial was averaged over the two minutes to obtain single oxygen and

carbon dioxide volumetric flow rates for each trial. The averaged values were divided by 60 to convert from units of mL $s^{-1}$ to units of mL $min^{-1}$. The average oxygen and carbon dioxide volumetric flow rates for each trial were then normalized by the respective subject's mass to get units of mL $kg^{-1}$ $min^{-1}$ and were labeled using the variables $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ respectively. The averaged volumetric flow rates per unit mass were then used to estimate metabolic rate (metabolic cost per unit time) per unit mass ($\mathrm{W\ kg^{-1}}$) using the equation $\dot{E} = 16.58\dot{V}_{O_2} + 4.51\dot{V}_{CO_2}$. Greater metabolic rate per unit mass represented higher energy expenditure while lower metabolic rate per unit mass represented lower energy expenditure. Throughout the rest of this document, metabolic rate per unit mass will be referred to as "metabolic rate" or "metabolic cost per unit time."

A more meaningful way of analyzing metabolic data is to analyze the data in terms of per unit distance instead of per unit time. To calculate metabolic cost per unit distance, the metabolic rate per unit mass, $\dot{E}$, was normalized by the subject's average walking speed calculated for the trial. Walking speed was calculated using the methods described in section 2.3 (Walking Speed Data Collection). Such a normalization resulted in the metabolic cost per unit distance per unit mass ($\mathrm{W\ m^{-1}\ kg^{-1}}$). Throughout the rest of this document, metabolic cost per unit distance per unit mass will be referred to as "metabolic cost per unit distance." The metabolic cost per unit distance is proportional to the energy required to travel a given distance.

**2.5 Overground Walking Trials**

The protocol for the following experiment was approved by the Ohio State University Institutional Review Board and all subjects participated with informed consent.

Overground walking trials with the cart were performed to determine the relationship between motor assistance level, walking speed, and the metabolic cost of walking. Before beginning experiments, a path on the fourth floor of Scott Laboratory at The Ohio State University was outlined and shown to each subject. The path was held constant for all subjects to reduce the effect of terrain and obstacles on the results of the experiments. Due to the configuration of Scott Laboratory, two types of paths were considered before beginning experiments. The first path type was a straight walkway that was approximately 150 ft (approximately 45.6 m) long. Though this path consisted mostly of straight-line walking, subjects would be required to turn 180 degrees multiple times in each trial due to the duration of the trials, which would cause subjects to slow their walking speeds significantly. In addition to altering walking speeds, it has been shown that turning increases the metabolic cost of walking [14]. Thus, to better understand how the cart affects subjects while walking, ensuring subjects walked continuously forward with minimal turning was desirable. Therefore, a second type of path that consisted of four 90-degree turns and four long straightaways was chosen instead. The two longer straightaways were the same length as the long straightaway described in the first path type and the shorter straightaways were approximately 62 ft (approximately 18.9 m) long. A dimensioned schematic of the chosen path can be seen in Figure 12.

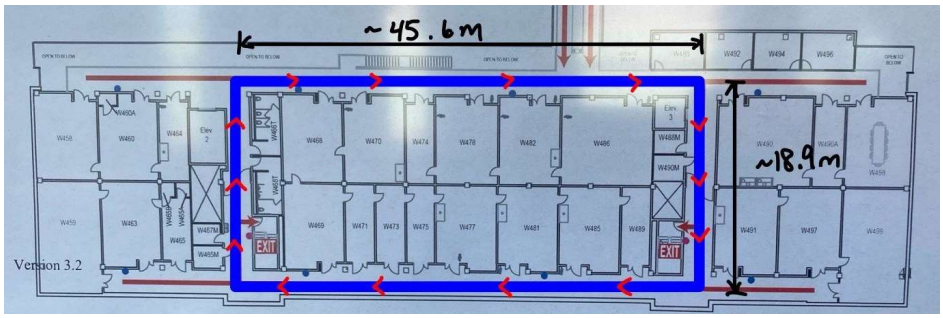


Figure 12. Dimensioned drawing of the closed loop walking path. The path was located on the fourth floor of Scott Laboratory.

Before beginning data collection, subjects were shown the path. If subjects were unfamiliar with Scott Laboratory and/or the path, subjects were asked to walk the path before beginning data collection. Once familiar with the path, six minutes of sitting resting metabolic rate data was collected for each subject. This trial was labeled Trial 1. Because the average walking metabolic rate for each trial was expected to be greater than the average resting metabolic rate, the average resting metabolic rate was used to verify the accuracy of the metabolic rate data collected throughout the experiment. Hence, if the average walking metabolic rate for a trial was determined to be significantly lower than the average resting metabolic rate from Trial 1, the metabolic rate data being collected would be considered invalid.

The order of trials 2 through 10 was randomized using the “randperm” function in MATLAB. One trial in trials 2 through 10 had subjects walk normally without the cart. Thus, the only device attached to subjects during this normal walking trial was the COSMED K5 wearable metabolic system. The purpose of this trial was to establish a baseline walking speed and metabolic cost of walking for each subject. The baseline values were used as reference values throughout data analysis. The difference between the baseline metabolic cost and the metabolic cost recorded for a given assistance level described whether the associated assistive

propulsive force increased or decreased the metabolic cost of walking. The same was true for walking speed.

Another of the final nine trials was dedicated to having subjects walk with the non-powered version of the cart. Thus, the batteries remained unplugged throughout the trial, which resulted in the brushless DC motor producing no assistive propulsive force. This trial was labeled as potentiometer setting 0. The remaining seven trials corresponded to potentiometer settings between 3.3 and 4.2. Table 1 below outlines the trial order for each of the five subjects.

Table 1. Trial order for each subject. The values in the table represent the potentiometer setting tested in each trial for each subject. The trial that corresponded to normal walking is denoted as "No cart" in the table.

| | **Subject** | | | | |
|---|---|---|---|---|---|
| **Trial #** | **1** | **2** | **3** | **4** | **5** |
| **1** | Sitting Resting | Sitting Resting | Sitting Resting | Sitting Resting | Sitting Resting |
| **2** | No cart | No cart | No cart | 3.75 | 4.20 |
| **3** | 0.00 | 0.00 | 0.00 | 3.30 | No cart |
| **4** | 4.20 | 4.20 | 4.20 | 3.90 | 0.00 |
| **5** | 3.45 | 3.45 | 3.45 | 4.05 | 3.75 |
| **6** | 3.30 | 3.30 | 3.30 | 3.60 | 4.05 |
| **7** | 3.90 | 3.90 | 3.90 | 0.00 | 3.30 |
| **8** | 3.75 | 3.75 | 3.75 | No cart | 3.90 |
| **9** | 3.60 | 3.60 | 3.60 | 3.45 | 3.45 |
| **10** | 4.05 | 4.05 | 4.05 | 4.20 | 3.60 |

Between each trial outlined in Table 1, subjects were permitted to rest as desired. No limits were placed on the length or frequency of breaks during the experiment.

## Chapter 3. Results

For visual purposes, the normal walking trial in which subjects walked normally without the cart was labeled as potentiometer setting -1. The trial in which subjects used the cart with the motor turned off was labeled as potentiometer setting 0.

### 3.1 Walking Speed

The average normal walking speed of the five subjects was 1.70 m $s^{-1}$. Though walking speed tended to increase with potentiometer setting, potentiometer setting 4.2 (the greatest assistance level) was the only potentiometer setting to increase the average walking speed of the five subjects from the average normal walking speed. Thus, the fastest average walking speed of the five subjects was 1.85 m $s^{-1}$ and corresponded to potentiometer setting 4.2. This maximum average walking speed was a 9.15% increase from the average normal walking speed of the five subjects. Conversely, the slowest average walking speed of the five subjects was 1.43 m $s^{-1}$ and corresponded to potentiometer setting 0 (non-powered version of the cart). This minimum walking speed was a 15.92% reduction from the average normal walking speed referenced earlier. Table 2 and Figures 13 and 14 below contain the results described above.

Table 2. Average walking speed of the five subjects for each assistance level. Percent difference measures the percent difference in average walking speed of a given assistance level from the no cart trial. The minimum and maximum values represent the minimum and maximum walking speeds recorded (across all five subjects).

| Potentiometer Setting | Walking Speed (m/s) | Percent Difference (%) | Minimum (m/s) | Maximum (m/s) |
|---|---|---|---|---|
| No cart | 1.70 | 0.00 | 1.46 | 1.80 |
| 0.00 | 1.43 | -15.92 | 1.05 | 1.74 |
| 3.30 | 1.51 | -11.26 | 1.29 | 1.79 |
| 3.45 | 1.52 | -10.18 | 1.29 | 1.69 |
| 3.60 | 1.56 | -7.86 | 1.32 | 1.79 |
| 3.75 | 1.53 | -9.98 | 1.31 | 1.85 |
| 3.90 | 1.64 | -3.12 | 1.48 | 1.87 |
| 4.05 | 1.67 | -1.48 | 1.53 | 1.86 |
| 4.20 | 1.85 | 9.15 | 1.59 | 2.06 |

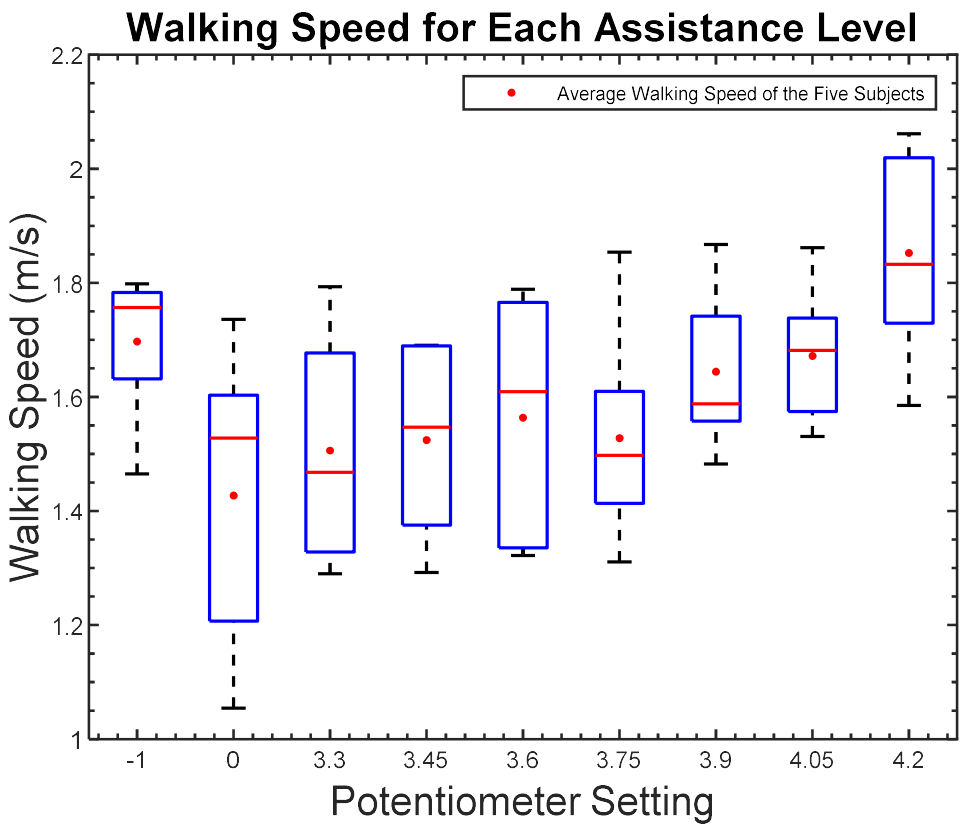


Figure 13. Box plot of the five subjects' walking speed for each assistance level.

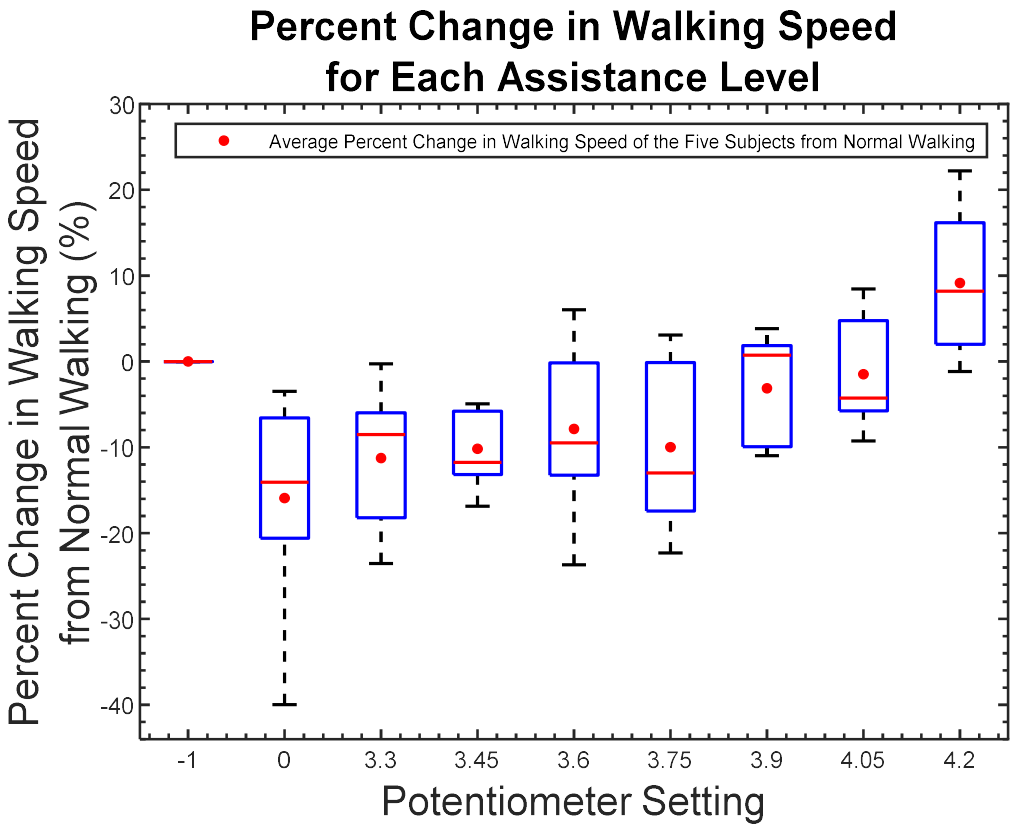


Figure 14. Box plot of the five subjects' percent change in walking speed from normal walking for each assistance level.

The individual minimum and maximum values described in Table 2 and visualized in the whiskers of Figures 13 and 14 demonstrate the range of walking speeds across the five subjects for each assistance level. Though only one potentiometer setting increased average walking speed, all subjects experienced an increase in walking speed for some potentiometer setting. Graphs containing subjects' individual walking speeds and percent changes in walking speed from normal walking for each assistance level are shown in Figures 19-28 in the Appendix.

### 3.2 Metabolic Rate

The average metabolic rate (metabolic cost per unit time) of the five subjects for normal walking was 4.52 W $kg^{-1}$. The average metabolic rate of the five subjects increased from normal

walking for all potentiometer settings except one. Thus, potentiometer setting 3.6, which corresponded to an average metabolic rate of 4.47 W $kg^{-1}$, was the only potentiometer setting that reduced the average metabolic rate from normal walking across the five subjects (-1.08%). Conversely, the greatest potentiometer setting of 4.2, which corresponded to an average metabolic rate of 5.34 W $kg^{-1}$, resulted in the greatest increase in metabolic rate (+18.13%). Table 3 and Figures 15 and 16 below contain the results described above.

Table 3. Average metabolic rate of the five subjects for each assistance level. Percent difference measures the percent difference in average metabolic rate of a given assistance level from the no cart trial. The minimum and maximum values represent the minimum and maximum metabolic rates recorded (across all five subjects).

| Potentiometer Setting | Metabolic Cost per Unit Time (W/kg) | % Difference | Minimum (W/kg) | Maximum (W/kg) |
|---|---|---|---|---|
| Sitting Resting | 1.51 | | 1.29 | 1.73 |
| No cart | 4.52 | 0.00 | 3.44 | 5.41 |
| 0.00 | 4.68 | 3.42 | 3.59 | 5.55 |
| 3.30 | 4.74 | 4.79 | 3.51 | 7.56 |
| 3.45 | 4.74 | 4.89 | 3.54 | 6.45 |
| 3.60 | 4.47 | -1.08 | 3.33 | 5.95 |
| 3.75 | 4.68 | 3.50 | 3.44 | 6.24 |
| 3.90 | 4.82 | 6.60 | 3.35 | 6.31 |
| 4.05 | 5.12 | 13.24 | 3.35 | 6.99 |
| 4.20 | 5.34 | 18.13 | 4.06 | 7.22 |

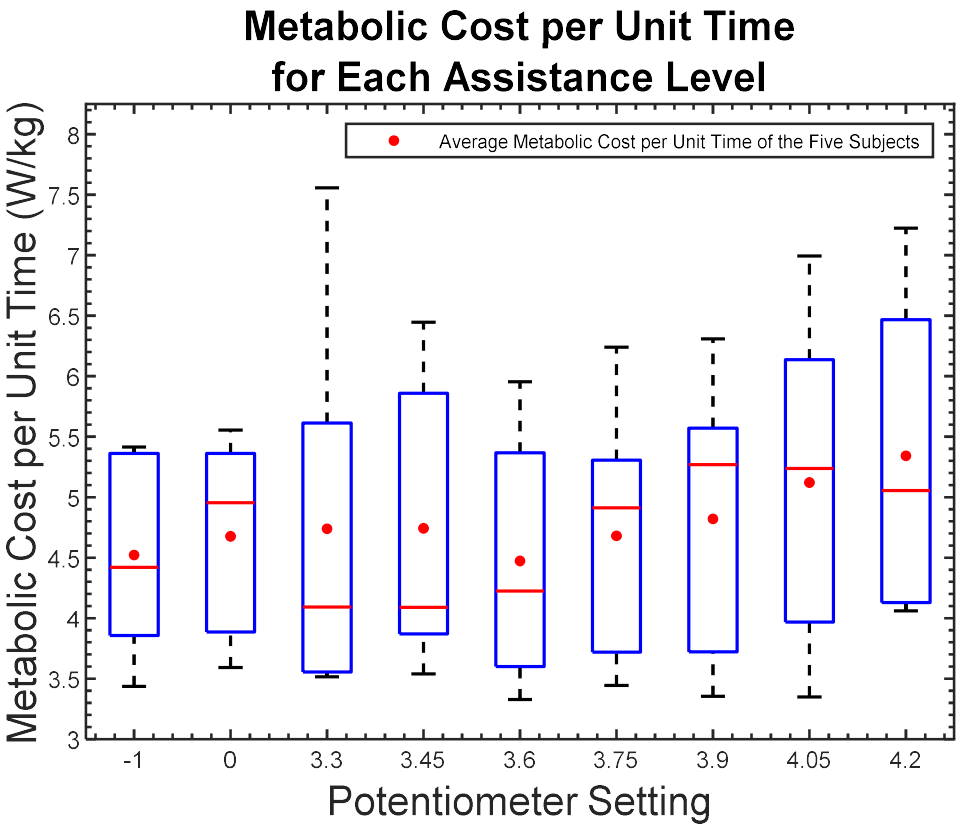


Figure 15. Box plot of the five subjects' metabolic rate for each assistance level.

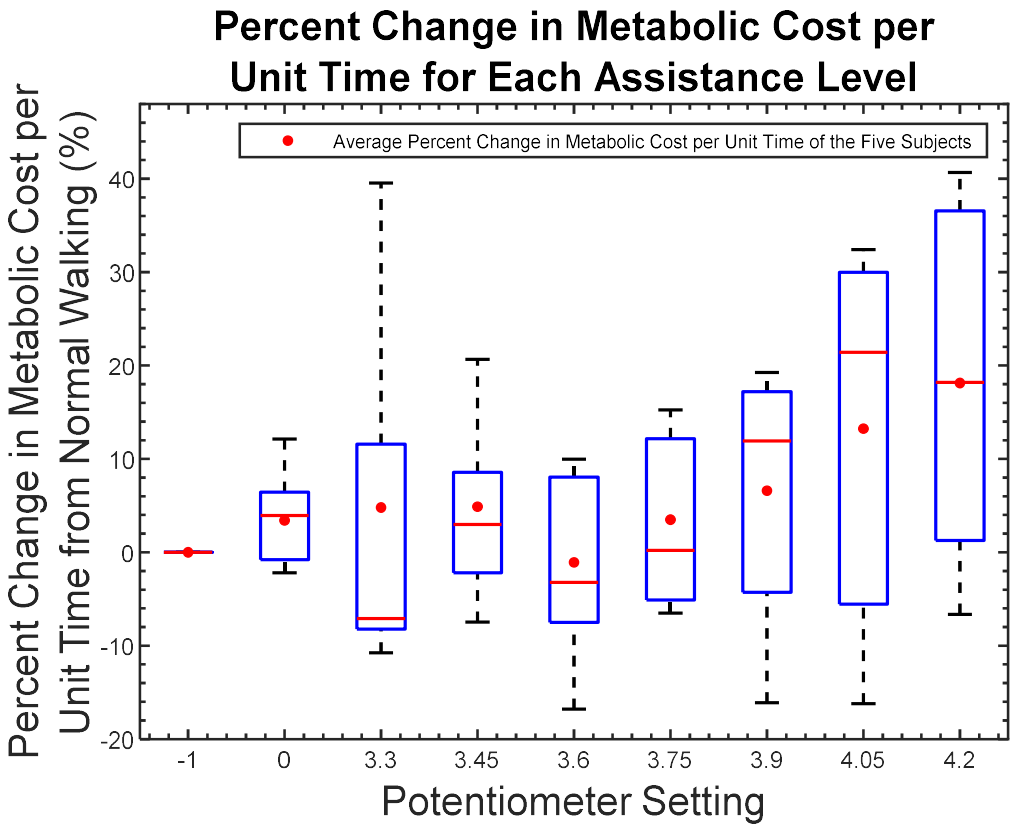


Figure 16. Box plot of the five subjects' percent change in metabolic rate from normal walking for each assistance level.

Table 3 and Figures 15 and 16 show that metabolic rate generally increased with potentiometer setting when observing the data averaged across the five subjects. However, the effect of potentiometer setting on metabolic rate varied between subjects. Four out of five subjects experienced a decrease in metabolic rate for some potentiometer setting, whereas one subject did not experience such a decrease for any potentiometer setting. Thus, this subject's metabolic rate increased for every assistance level. Contrarily, one subject saw a decrease in metabolic rate for all but one potentiometer setting (4.2). This wide variance in metabolic rates recorded for each assistance level is demonstrated by the individual minimum and maximum values in Table 3 and the whiskers in Figures 15 and 16. For a more detailed understanding of

the variance between subjects, graphs containing subjects' individual metabolic rates and percent changes in metabolic rate from normal walking can be found in Figures 29-38 in the Appendix.

Regarding the non-powered version of the cart, the average metabolic rate of the five subjects increased from normal walking by 3.41%. However, though three subjects experienced increases in metabolic rate from normal walking when walking with the non-powered version of the cart (+12.23%, +4.54%, 3.94%), the other two subjects experienced relatively small decreases (-0.30% and -2.18%), which further emphasized the differences in how the cart affected walking metabolic rate between different subjects.

### 3.3 Metabolic Cost per Unit Distance

The average metabolic cost per unit distance of the five subjects for normal walking was 2.65 W $m^{-1}$ $kg^{-1}$. The average metabolic cost per unit distance of the five subjects increased from normal walking for all potentiometer settings. Therefore, the cart did not reduce the energy required to travel a given distance for any of the tested assistance levels. The non-powered version of the cart corresponded to the greatest average metabolic cost per unit distance (3.30 W $m^{-1}$ $kg^{-1}$) across the five subjects, which was a 24.47% increase from normal walking. Though no single potentiometer setting reduced the average metabolic cost per unit distance of the five subjects from normal walking, potentiometer setting 3.6 corresponded to the smallest increase in average metabolic cost (+7.38%) from normal walking with a cost of 2.85 W $m^{-1}$ $kg^{-1}$. Table 4 and Figures 17 and 18 below contain the results described above.

Table 4. Average metabolic cost per unit distance of the five subjects for each assistance level. Percent difference measures the percent difference in metabolic cost per unit distance of a given assistance level from the no cart trial. The minimum and maximum values represent the minimum and maximum metabolic costs per unit distance recorded (across all five subjects).

| **Potentiometer Setting** | **Metabolic Cost per Unit Distance (J/(m kg))** | **Percent Difference (%)** | **Minimum (J/(m kg))** | **Maximum (J/(m kg))** |
|---|---|---|---|---|
| No cart | 2.65 | 0.00 | 2.28 | 3.01 |
| 0.00 | 3.30 | 24.47 | 2.86 | 3.78 |
| 3.30 | 3.09 | 16.68 | 2.43 | 4.21 |
| 3.45 | 3.08 | 16.10 | 2.57 | 3.81 |
| 3.60 | 2.85 | 7.38 | 2.36 | 3.39 |
| 3.75 | 3.06 | 15.57 | 2.38 | 3.75 |
| 3.90 | 2.91 | 9.75 | 2.11 | 3.38 |
| 4.05 | 3.06 | 15.29 | 1.99 | 3.82 |
| 4.20 | 2.89 | 8.90 | 2.07 | 3.94 |

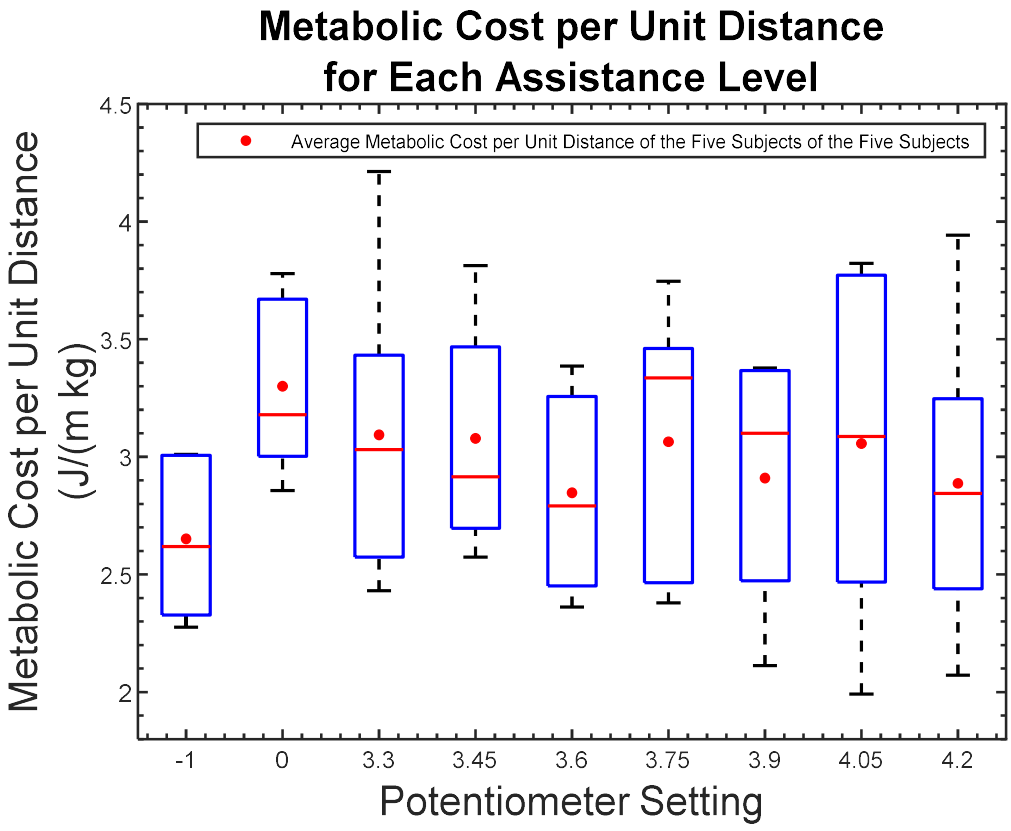


Figure 17. Box plot of the five subjects' metabolic cost per unit distance for each assistance level.

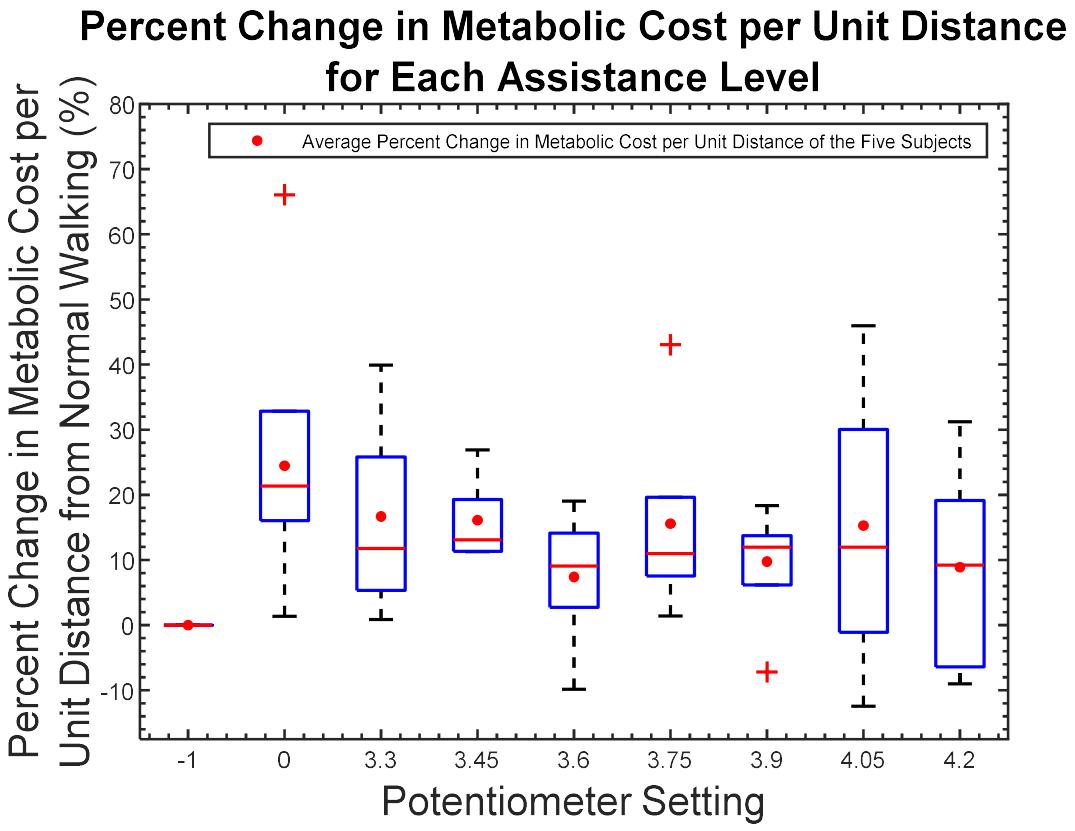


Figure 18. Box plot of the five subjects' percent change in metabolic cost per unit distance from normal walking for each assistance level.

Though Table 4 and Figures 17 and 18 show that the average metabolic cost per unit distance of the five subjects increased from normal walking for every potentiometer setting, some subjects did experience decreases in metabolic cost per unit distance for various potentiometer settings. For example, two subjects experienced reductions of 9.84% and 5.53% in metabolic cost per unit distance for one potentiometer setting (3.6 and 4.2 respectively). Additionally, one subject experienced reductions in metabolic cost per unit distance of 7.19%, 12.47%, and 8.99% for potentiometer settings 3.9, 4.05, and 4.2 respectively. Thus, three out of five subjects experienced some reduction in metabolic cost per unit distance for at least some potentiometer setting. Such results are highlighted in the individual minimum and maximum

values described in Table 4 and visualized in the whiskers of Figures 17 and 18. For a more detailed understanding of the variance between subjects, graphs containing subjects' individual metabolic costs per unit distance and percent changes in metabolic cost per unit distance from normal walking can be found in Figures 39-48 in the Appendix.

# Chapter 4. Discussion

## 4.1 Walking Speed

Typical human walking speeds range from 1-2 m $s^{-1}$. Most of the collected walking speeds were within the expected range of 1-2 m $s^{-1}$. The only outliers were the walking speeds for two subjects when walking with the greatest potentiometer setting of 4.2 (2.06 m $s^{-1}$ and 2.01 m $s^{-1}$). Most of the calculated walking speeds lying in the expected range added validity to the collected walking speed data.

The average walking speed of the five subjects tended to increase with potentiometer setting. This trend was likely due to the greater forward force applied to subjects at greater assistance levels. However, the only potentiometer setting to increase the average walking speed of the five subjects from normal walking was the greatest potentiometer setting of 4.2. Thus, when used at the tested assistance levels, the cart typically decreased subjects' walking speed from normal walking. Such reductions in walking speed were likely due to the rolling resistance and inertia of the cart. The rolling resistance increased the force applied to subjects in the opposite direction of travel (resistive force), which would decrease walking speed. The inertia of the cart could have contributed to oscillatory motion of the cart, which could have negatively affected subjects' stability while walking. These trends partially aligned with previous results. Mattar showed that walking speed typically increased with assistance level, which agrees with the results in this research. However, Mattar also demonstrated that walking with the cart typically increased walking speed compared to normal walking. Such results directly contradict the results of this study. These differences may be due to how walking speed was calculated. Mattar found walking speed by timing how long it took each subject to walk down a 50 m long

hallway. Contrarily, the walking speed data above was calculated by timing how long it took subjects to walk 2.76 m [13]. Though calculating walking speed using a longer reference length could have reduced error, error in these experiments was best reduced by recording the walking speed for each lap. Because subjects would walk multiple laps around the path throughout each trial, subjects would also pass the camera multiple times. This repetition allowed for multiple walking speed samples to be recorded for each trial, which increased the accuracy of the walking speed data. As stated in section 2.3 (Walking Speed Data Collection), the samples associated with each trial were averaged to obtain one average walking speed for each trial.

The non-powered version of the cart decreased walking speed from normal walking for all subjects. As stated earlier, this was likely due to the added weight subjects had to propel forward while walking with the cart. The effects of rolling resistance were the greatest for the non-powered version of the cart compared to the other versions because the non-powered version of the cart enacted no assistive propulsive force on the subjects. This trend aligned with previous results from Mattar. Mattar found that the non-powered version of the cart decreased walking speed from normal walking for all four subjects [13].

### 4.2 Metabolic Rate

All the collected walking metabolic rate data was greater than the resting metabolic rate. This trend validated the walking metabolic rate data because if the walking metabolic rate was below the resting metabolic rate, an error may have occurred in the procedure, or a faulty piece of equipment may have been used.

For all but one potentiometer setting, the cart increased the average metabolic rate of the five subjects. The average metabolic rate typically increased with potentiometer setting. This trend may be due to the additional resistance provided by the cart to subjects and the effect the cart had on subjects' walking mechanics. Though greater assistance levels should have helped reduce the effects of rolling resistance on subjects, the forward force may have negatively affected subjects' walking mechanics in such a way that overshadowed the effects of the forward force on rolling resistance. Such trends suggest that the cart may be unable to reduce metabolic rate. However, the results also suggest that there may be a potentiometer setting near 3.6 that best reduces metabolic rate. Zimmerman previously collected metabolic rate data from subjects walking with the cart on a treadmill while the cart was tied to a stationary handlebar at the front of the treadmill. Zimmerman found that subjects' metabolic rate decreased when walking at 1.2 m $s^{-1}$ on a treadmill. Because few walking speeds in this study closely aligned with the speed tested by Zimmerman, it is difficult to compare the two results and to determine whether the cart could reduce the metabolic cost per unit time of overground walking [1].

The non-powered version of the cart typically increased metabolic rate compared to normal walking. Two subjects experienced a decrease in metabolic rate when walking with the non-powered version of the cart. However, such reductions were relatively small. Therefore, the non-powered version of the cart did not provide enough assistance to subjects to decrease the metabolic cost per unit time of walking. Such results highlighted the importance of the motor and the forward force the motor provided.

It is important to recognize the differences in how the cart affected each subject's metabolic rate while walking. One subject experienced an increase in metabolic rate for every potentiometer setting while another subject only experienced an increase in metabolic rate for one potentiometer setting. Overall, we found that four out of five subjects had at least one potentiometer setting that reduced their metabolic rate. Such results demonstrate the differences in how each subject interacted with the cart as well as the potential drawbacks of reporting average data. In previous studies involving the cart, metabolic rate would decrease if subjects were instructed to lean back into the cart while walking [1]. Such instructions were not provided in this study, which may have increased the variability of the effects of the cart on metabolic rate between subjects.

### 4.3 Metabolic Cost per Unit Distance

The average metabolic cost per unit distance across the five subjects increased for all assistance levels when compared to normal walking. This increase was likely due to the added rolling resistance provided by the cart. However, though all potentiometer settings increased the metabolic cost per unit distance of walking, potentiometer setting and metabolic cost per unit distance had little correlation. Thus, as potentiometer setting increased, metabolic cost per unit distance remained relatively constant when averaged across the five subjects. These results show that the cart increases average metabolic cost per unit distance from normal walking. On the other hand, we found that three out of five subjects had some potentiometer setting that decreased the metabolic cost per unit distance of walking. Such a finding is promising and we hypothesize that a slightly better engineered cart or providing subjects with a longer training period may reduce metabolic cost for even more subjects.

The non-powered version of the cart consistently increased metabolic cost per unit distance. Hence, no subject experienced a reduction in metabolic cost per unit distance from normal walking when walking with the non-powered version of the cart. Therefore, the non-powered version of the cart negatively affected metabolic cost per unit distance. Such a negative effect was likely due to rolling resistance and/or the way the cart altered subjects' walking mechanics.

### 4.4 Sources of Error

The first potential source of error lied in the method used to record walking speed. Walking speed was recorded using a video and a reference length. The scrubbing function used in the video editor to determine how long it took subjects to traverse the reference length was of poor quality. It was impossible to acquire the exact time subjects crossed the beginning and end of the reference length because the scrubbing would only allow viewing in increments of approximately 0.14 seconds. In addition to the poor video scrubbing, the reference length was relatively short (2.76 m). To increase the accuracy of the walking speed data, a longer reference length would have been beneficial. The longer subjects spent in the reference frame, the less of an impact the poor scrubbing function would have had on the walking speed data.

A second potential source of error was the obstacles on the walking path. At points along the path, there were heavy machinery and trash bins. These obstacles were mainly located at the turning locations, which increased the sharpness of the turns. Such obstacles could have affected walking speed and the metabolic cost of walking. Additionally, because the path was a public space, pedestrians would sometimes be on the path during experiments. A few times

throughout testing, groups of pedestrians blocked or slowed subjects for small points in time. Such speed changes were unfavorable for the collection of metabolic data.

A third potential source of error was condensation in the COSMED K5 mask. Experiments lasted approximately two hours each. Some subjects did not remove the mask for the entire experiment. Once testing concluded and these subjects removed the mask, condensation was seen inside the mask. Water droplets could affect the metabolic data due to the sensitivity of the turbine used by COSMED to measure flow rate.

A fourth potential source of error was the experimental procedure. The first three subjects completed testing with the same trial order. Though the trial order was randomized such that the assistance levels were randomized throughout each subject's experiment, the trial order should have also been randomized between subjects. The trial order was only fully randomized for the final two subjects such that their trial order did not match any other subject's trial order. Such randomization was necessary to reduce the effects of the order of the trials on the results from the experiments. This randomization accounted for fatigue and the adaptation required to become familiar with the cart during the late and early trials respectively.

The final potential source of error was the type of subject tested. The cart was meant to be a rehabilitation device, which means that users would likely have a movement impairment. However, this study only tested healthy subjects with no movement impairments. The walking speed and metabolic cost trends may be different if subjects were not healthy individuals. Thus, the effects of the cart highlighted in this study may be different for those who struggle to independently walk.

## Chapter 5. Conclusion

Many currently used simple assistive walking devices have been shown to increase the metabolic cost of walking [7]. In this study, metabolic cost was used as a metric for effectiveness of assistive walking devices because such devices have been designed to provide a mechanical advantage to the user. Due to this mechanical advantage, it was expected that the metabolic cost of a user walking with an assistive device would decrease compared to when walking without the device. This research studied the effects of a previously developed assistive walking device on the metabolic cost of walking and walking speed to determine the effectiveness of the device. The assistive walking device was developed with the goals of being mechanically simple, easy to model, strong enough to support the user, easily maneuverable, easily utilized by users of various sizes, powerful, safe, and throttleable [1]. The device was a cart-like structure constructed using extruded aluminum T-slot bars that sat on four caster wheels. Subjects attached the cart to themselves using a gait belt and four springs.

Previous studies involving the cart analyzed the effect of the cart on metabolic rate and walking speed. One study analyzed metabolic data for the non-powered version of the cart during treadmill walking. Following studies analyzed walking speed data for the powered version of the cart for overground walking.

Therefore, to further study the cart, metabolic and walking speed data was collected from five subjects while they overground walked with the cart. The goals of this research were to upgrade the cart to improve the human-machine interaction, to quantify the effect of the cart on the metabolic cost of walking, and to understand the effect of the cart on walking speed. To achieve these goals, first, preliminary testing was performed to determine how the cart could

be improved. The location of subjects with respect to the cart was altered by replacing the springs that attached subjects to the cart. Subjects were biased forward to decrease the risk of contacting the rear rod holding the motor. Second, metabolic and walking speed data was collected from five subjects walking with the cart at eight different assistance levels. The data collected when walking with the cart was compared directly to the metabolic cost and walking speed recorded when walking without the cart. Therefore, this study consisted of nine six-minute walking trials where metabolic and walking speed data was collected. Each trial was associated with a different potentiometer setting. Greater potentiometer settings were associated with greater forward forces being applied to subjects via the brushless DC motor on the back of the cart and vice versa.

When averaged across the five subjects and compared to normal walking, the cart decreased walking speed for all potentiometer settings except one. Additionally, walking speed was generally shown to increase with potentiometer setting. The average metabolic rate of the five subjects increased from normal walking for all potentiometer settings but one. Like walking speed, average metabolic rate was generally shown to increase with potentiometer setting. Lastly, the cart increased the average metabolic cost per unit distance of the five subjects for all potentiometer settings when compared to normal walking. Average metabolic cost per unit distance remained relatively constant with respect to potentiometer setting.

While average metabolic costs typically increased or remained constant, we found that four out of five subjects showed a decrease in metabolic rate for some potentiometer setting and three out of five subjects showed a decrease in metabolic cost per unit distance for some potentiometer setting when compared to normal walking. These results show that the cart has

some potential. Thus, we may need the cart to be better engineered or to give subjects additional training time to result in a more uniform reduction in, specifically, the metabolic cost per unit distance of walking across all subjects. More research is needed to fully understand the effects of the cart on subjects when overground walking.

First, future research should include more subjects. More subjects would result in better averaged metabolic cost and walking speed data, which would then better illustrate the effectiveness of the cart. Second, additional research should test more assistance levels. The assistance levels tested in this study were chosen by examining previous studies on the cart. However, the results suggest that testing more, lower, potentiometer settings may help better illustrate how the cart affects the metabolic cost of walking. Additionally, testing a more discretized sample of potentiometer settings would help to better understand the relationship between metabolic cost and potentiometer setting. The results suggest that there may be a potentiometer setting near 3.6 that best reduces the metabolic cost per unit time of walking. Third, additional research should capture better quality walking speed data. Potential ways to capture better walking speed data would be to use accelerometers or a motion capture system. Accelerometers would provide the walking speed profile throughout the entire trial, while most typical motion capture systems would only be able to be used at certain points along the path. Fourth, future work should collect metabolic cost data for normal treadmill walking at the speeds recorded in this study. This future work would allow for the metabolic cost of walking with the cart at a given speed to be compared to the metabolic cost of walking normally, without the cart, at the same speed. Such an analysis would help determine the effects of the cart on metabolic cost for a given walking speed. Finally, future work should recruit subjects

with movement impairments to better understand the effectiveness of the cart on its target population. The cart may have negatively affected certain subjects in some instances because all subjects were healthy adults with no movement impairments. Thus, the population in this study did not accurately represent the target users of the cart.

Overall, future work should expand upon the research outlined in this thesis by recruiting more subjects, testing more assistance levels, collecting better walking speed data, collecting metabolic data for treadmill walking at the walking speeds seen in this study, and recruiting subjects with movement impairments. These improvements would increase the understanding of how the cart affects the metabolic cost of walking and walking speed. Understanding such relationships is critical in understanding the effectiveness of the cart and determining whether the cart is a viable replacement for currently used assistive walking devices.

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## Appendix

Table 5. Properties of the new springs.

| McMaster-Carr Part Number | Stiffness (N/m) | Length (m) | Outer Diameter (m) | Wire Diameter (m) |
|---|---|---|---|---|
| 9432K76 | 753 | 0.127 | 0.0127 | 0.00160 |

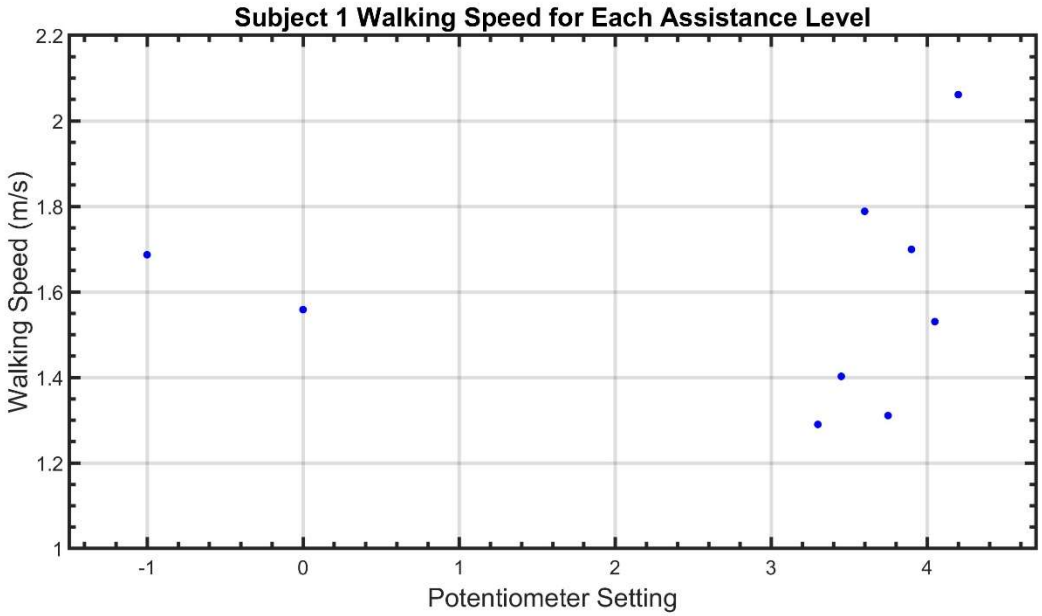


Figure 19. Graph of Subject 1's walking speed for each assistance level.

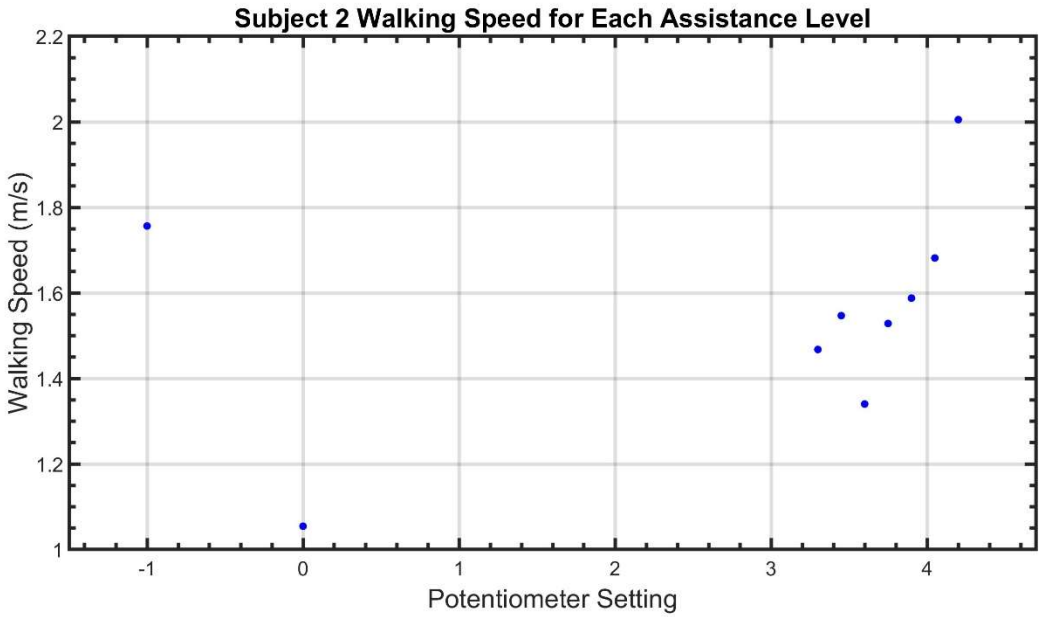


Figure 20. Graph of Subject 2's walking speed for each assistance level.

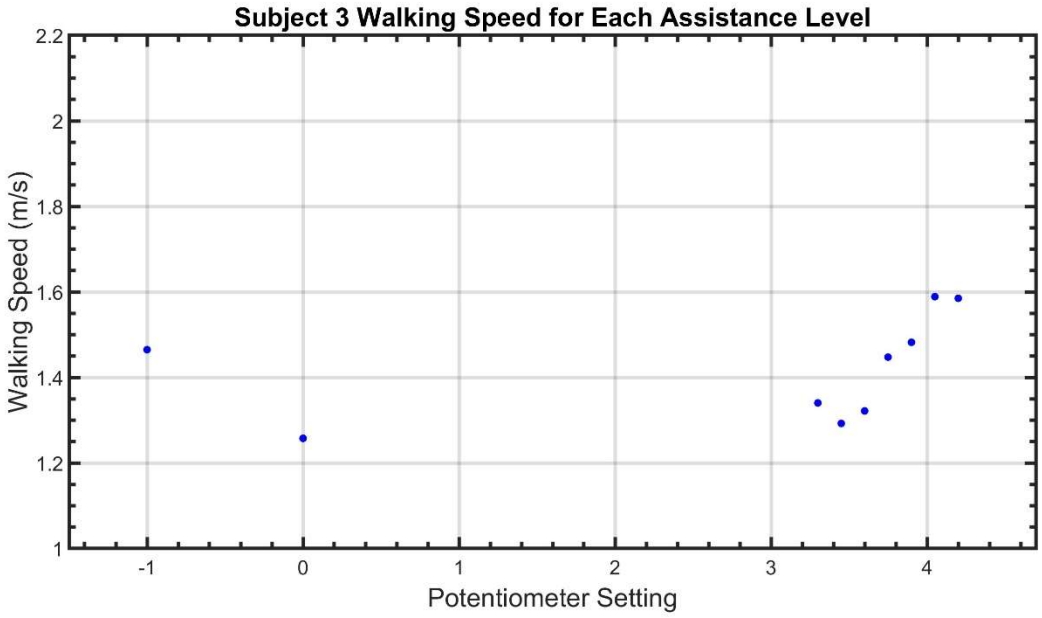


Figure 21. Graph of Subject 3's walking speed for each assistance level.

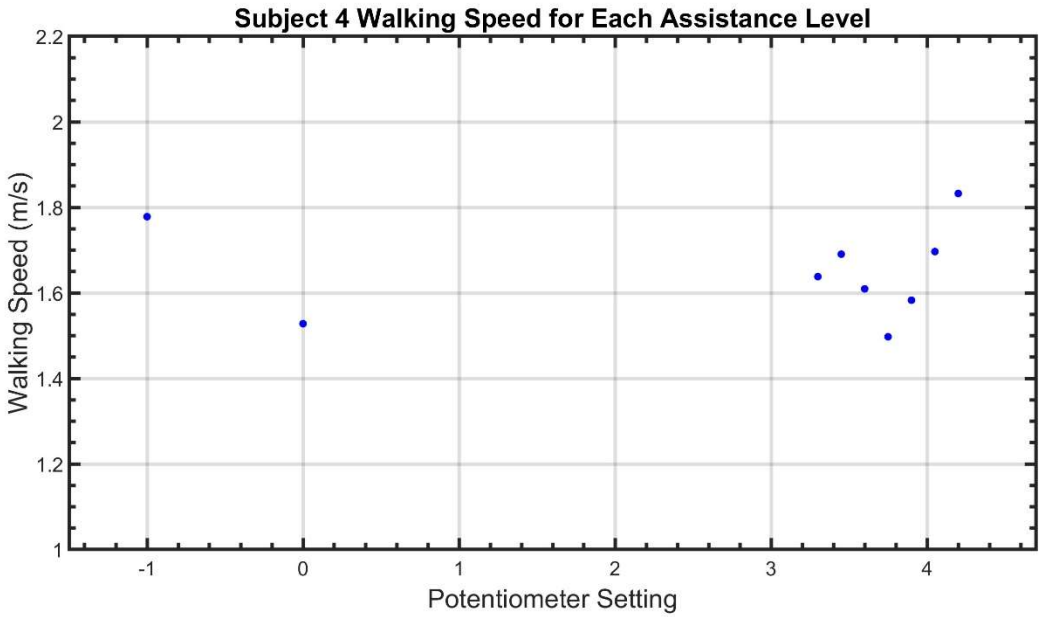


Figure 22. Graph of Subject 4's walking speed for each assistance level.

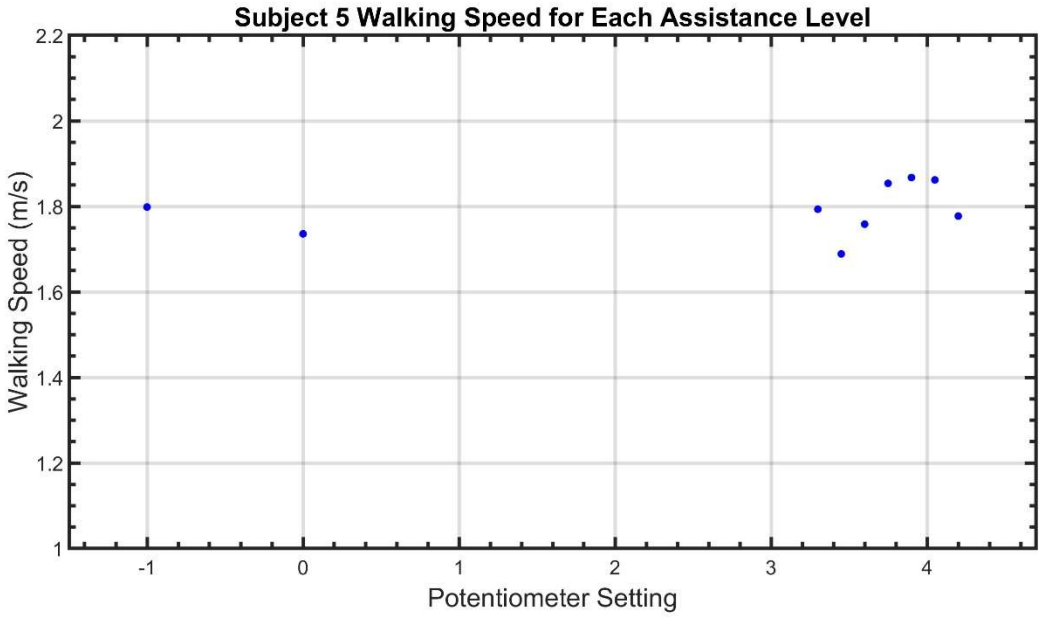


Figure 23. Graph of Subject 5's walking speed for each assistance level.

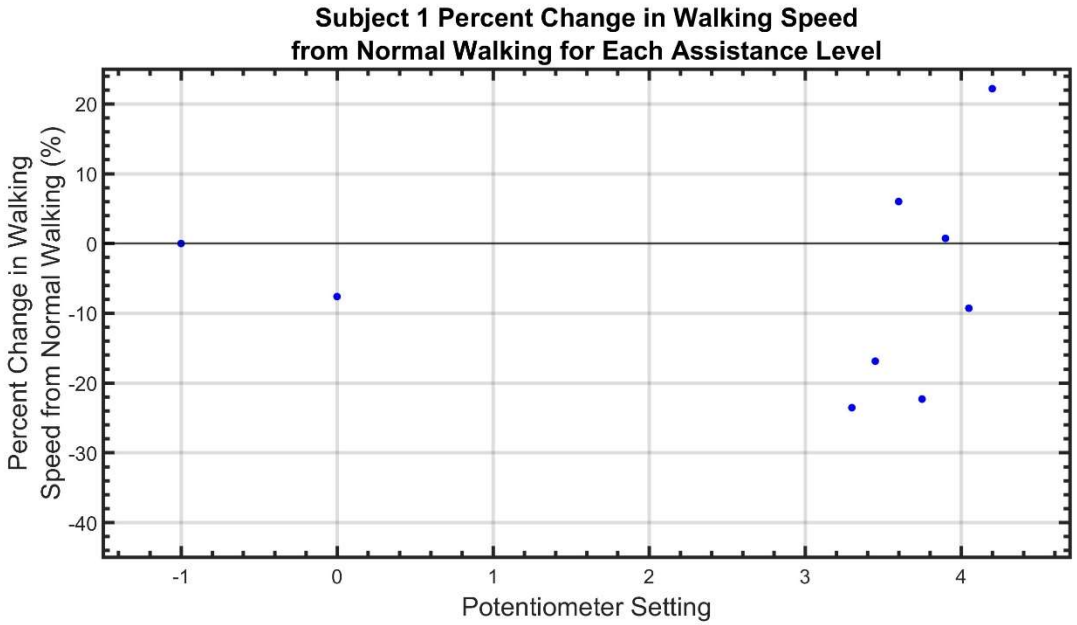


Figure 24. Graph of Subject 1's percent change in walking speed from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

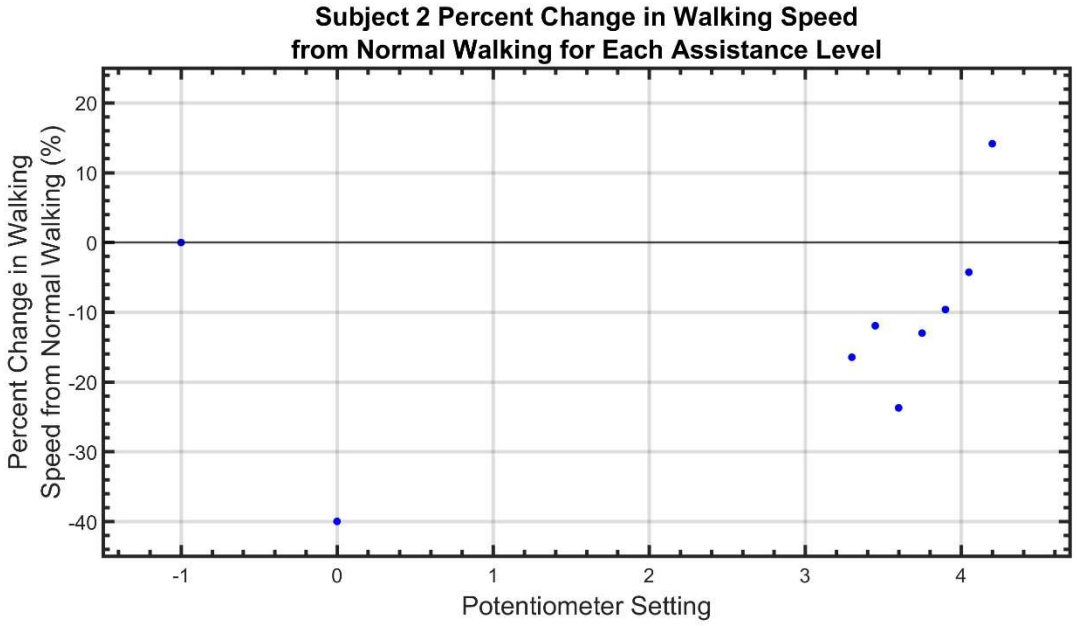


Figure 25. Graph of Subject 2's percent change in walking speed from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

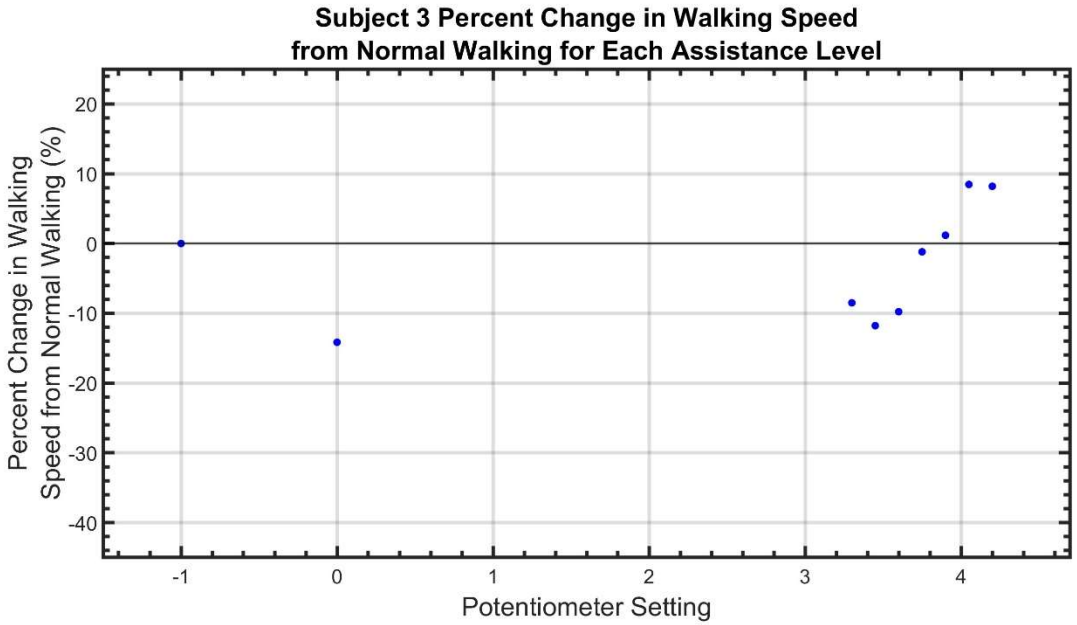


Figure 26. Graph of Subject 3's percent change in walking speed from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

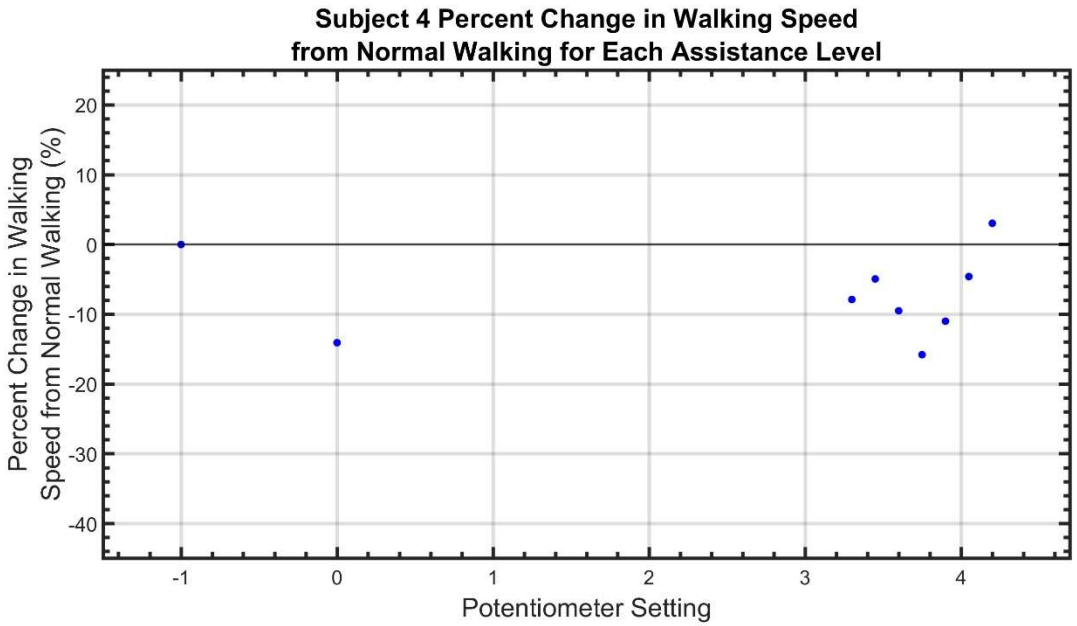


Figure 27. Graph of Subject 4's percent change in walking speed from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

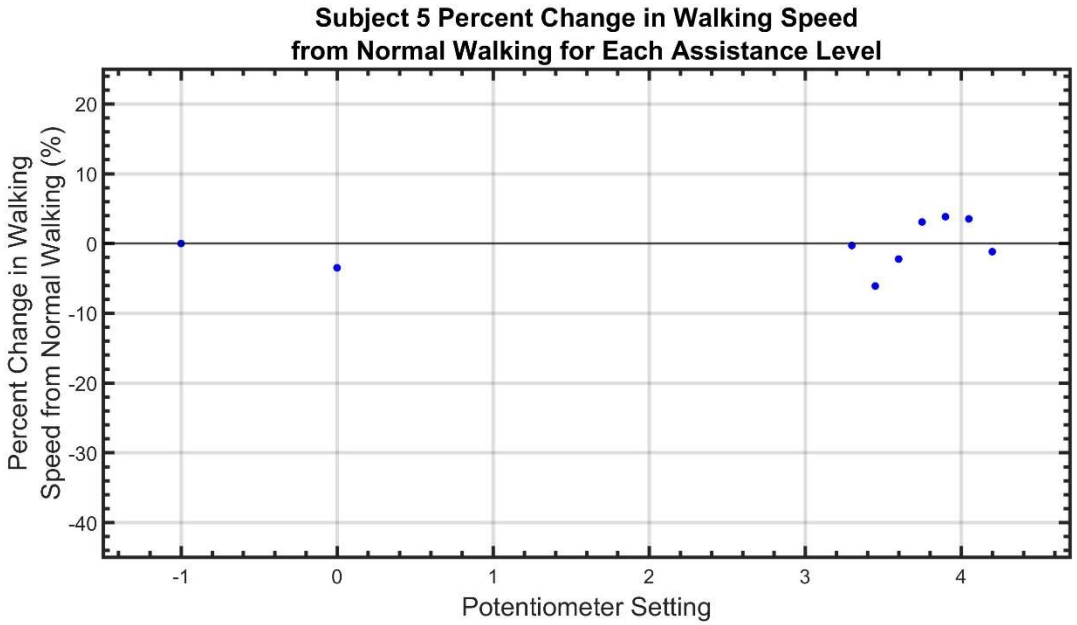


Figure 28. Graph of Subject 5's percent change in walking speed from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

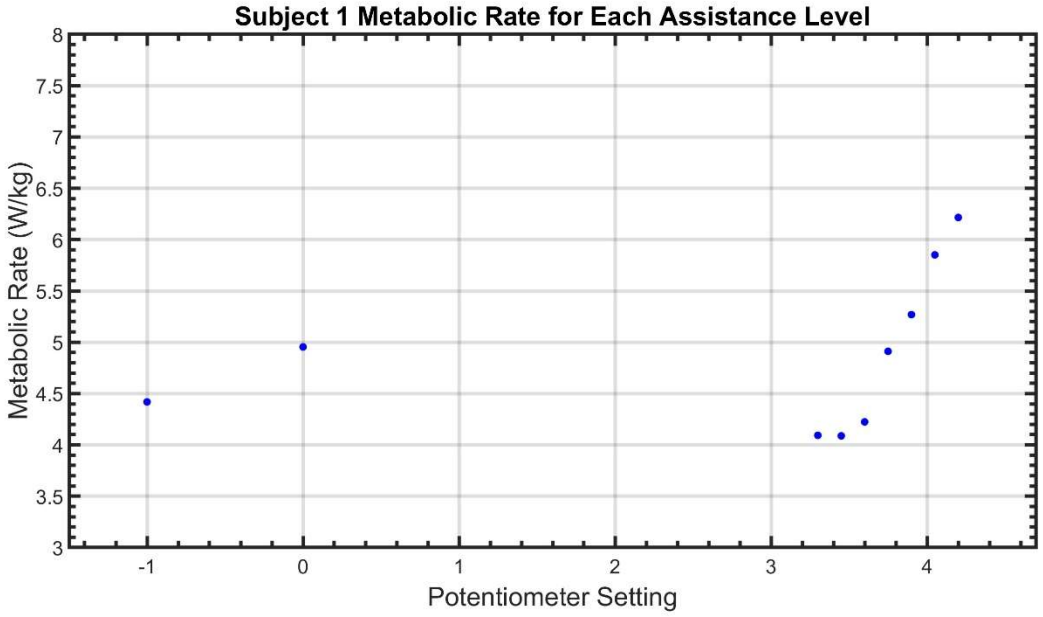


Figure 29. Subject 1's metabolic rate for each assistance level.

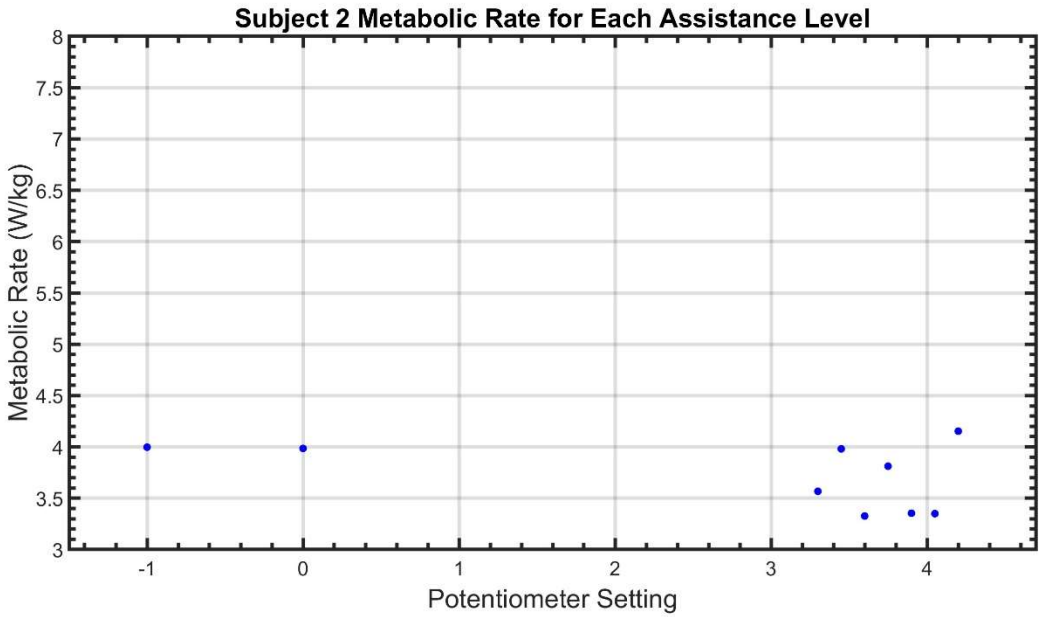


Figure 30. Subject 2's metabolic rate for each assistance level.

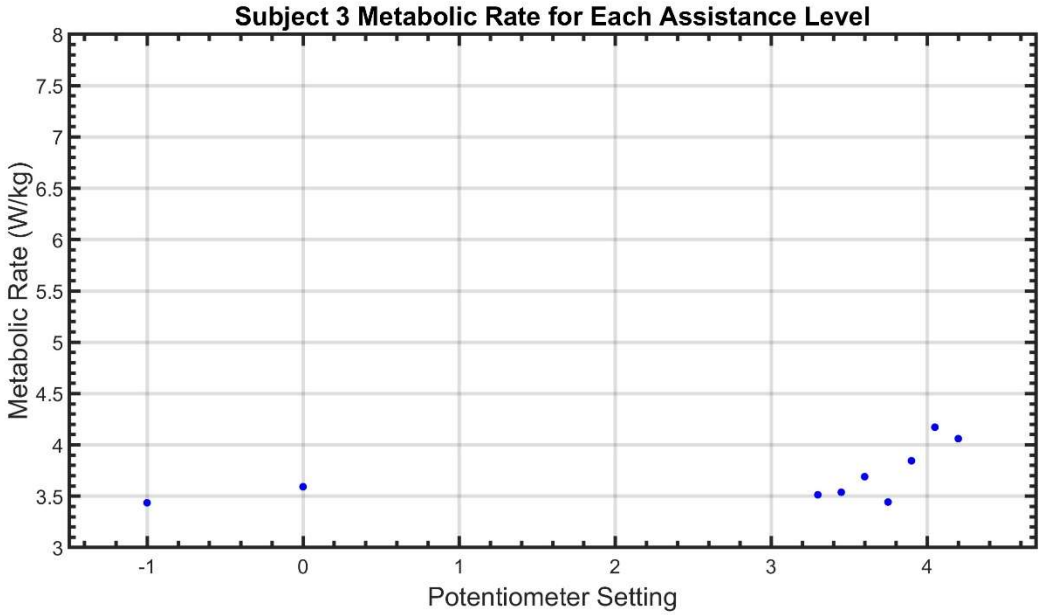


Figure 31. Subject 3's metabolic rate for each assistance level.

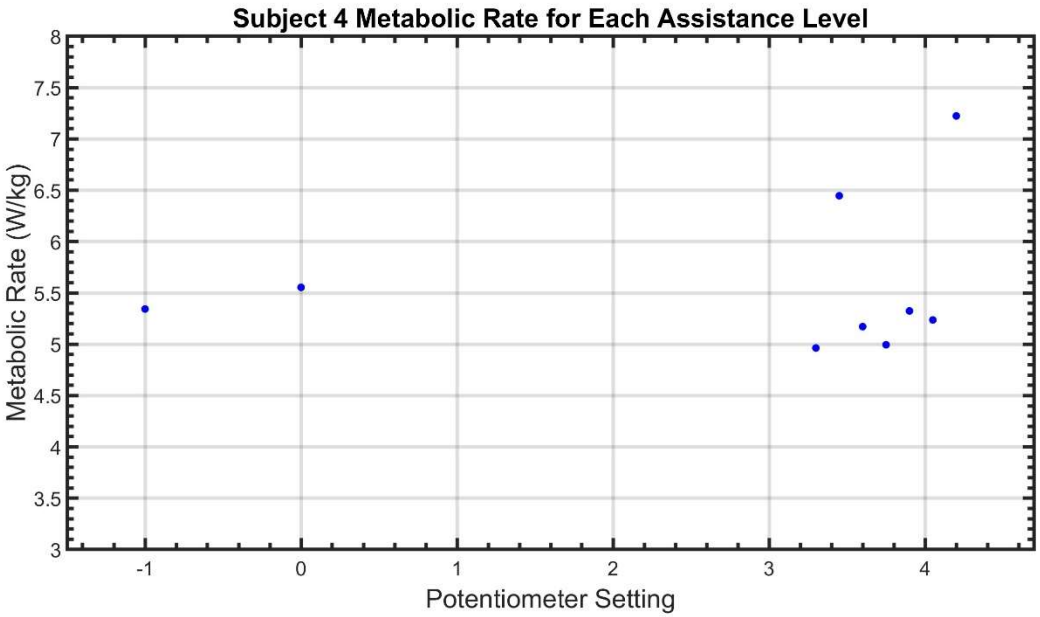


Figure 32. Subject 4's metabolic rate for each assistance level.

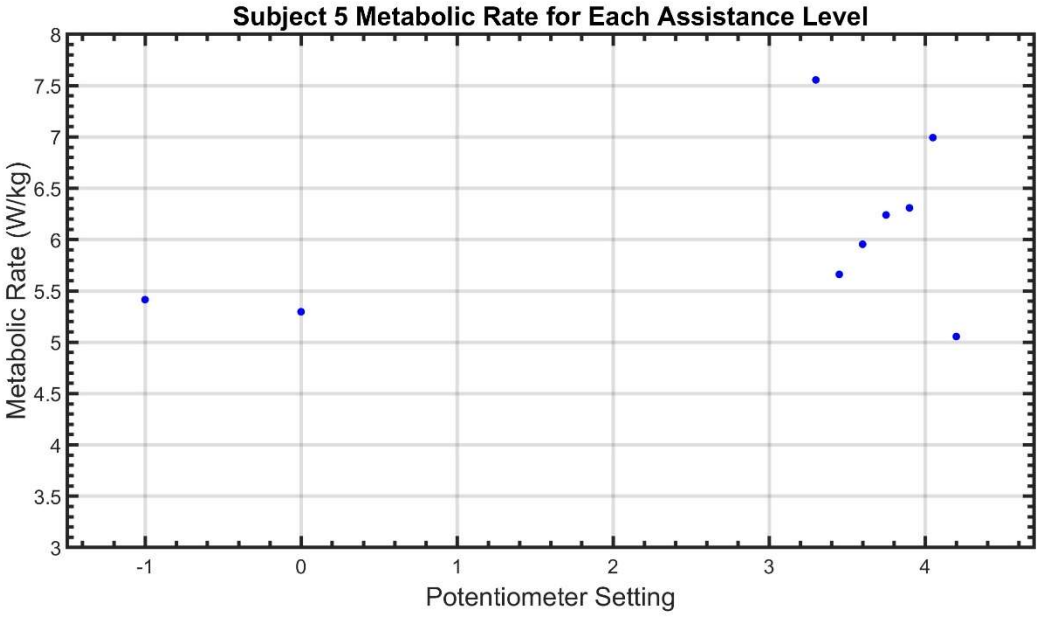


Figure 33. Subject 5's metabolic rate for each assistance level.

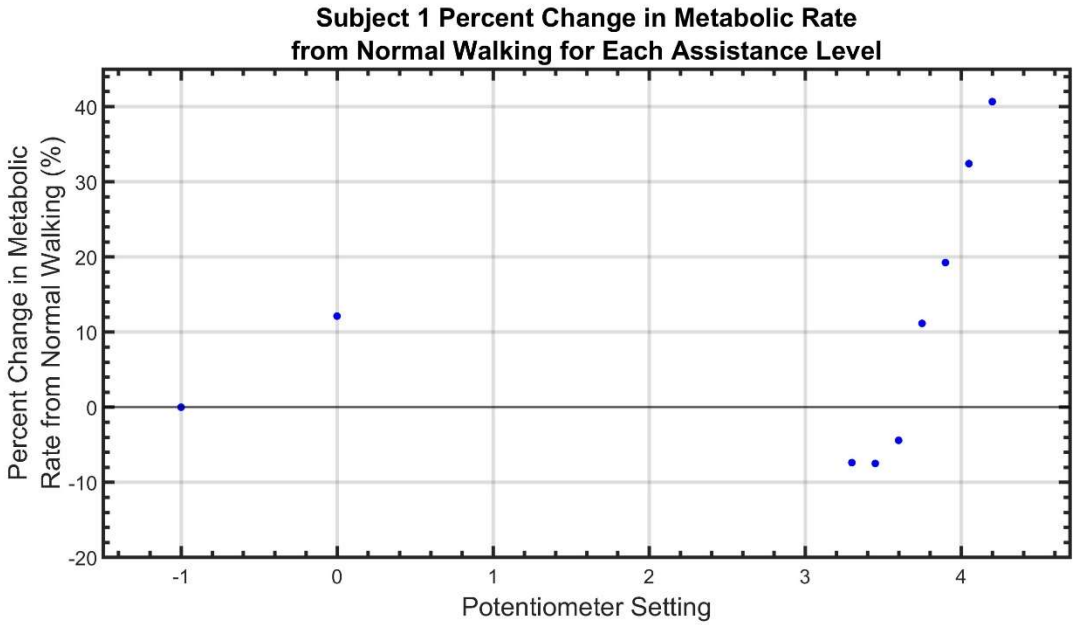


Figure 34. Subject 1's percent change in metabolic rate from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

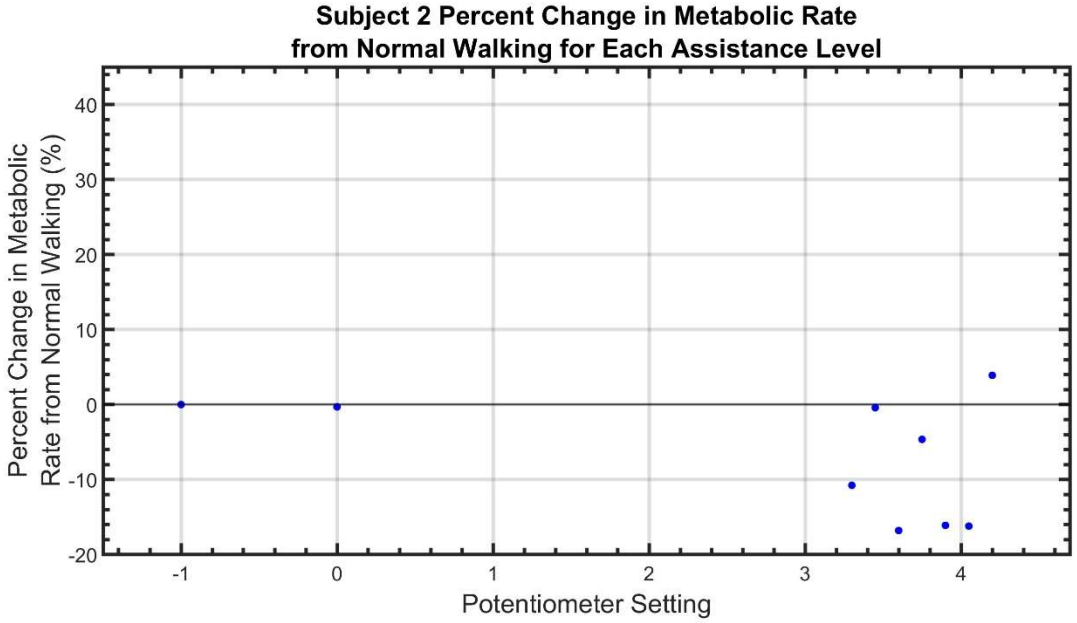


Figure 35. Subject 2's percent change in metabolic rate from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

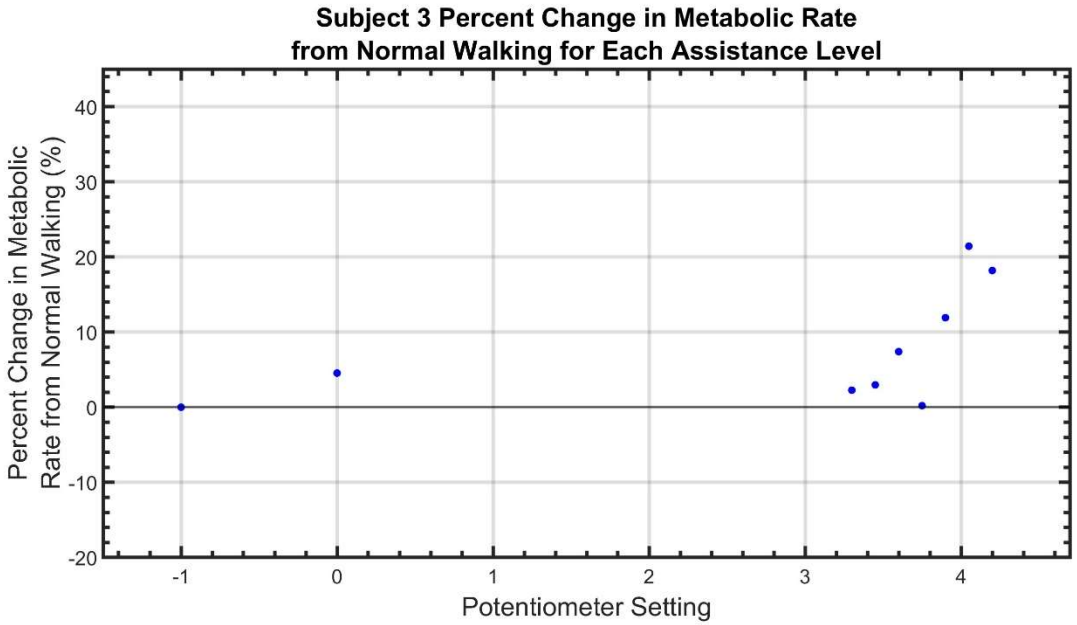


Figure 36. Subject 3's percent change in metabolic rate from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

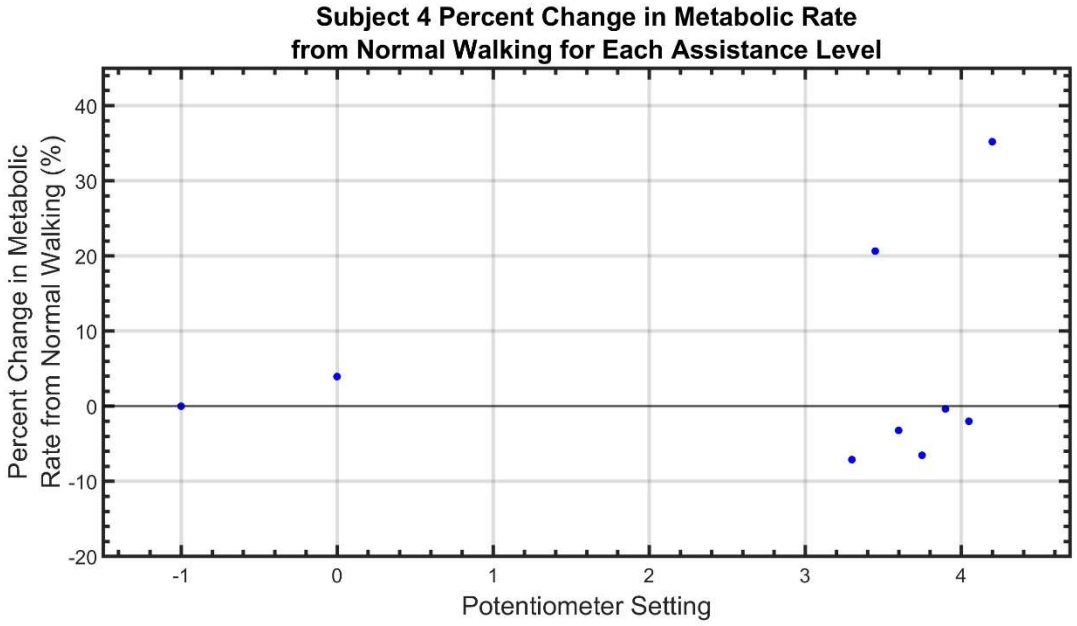


Figure 37. Subject 4's percent change in metabolic rate from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

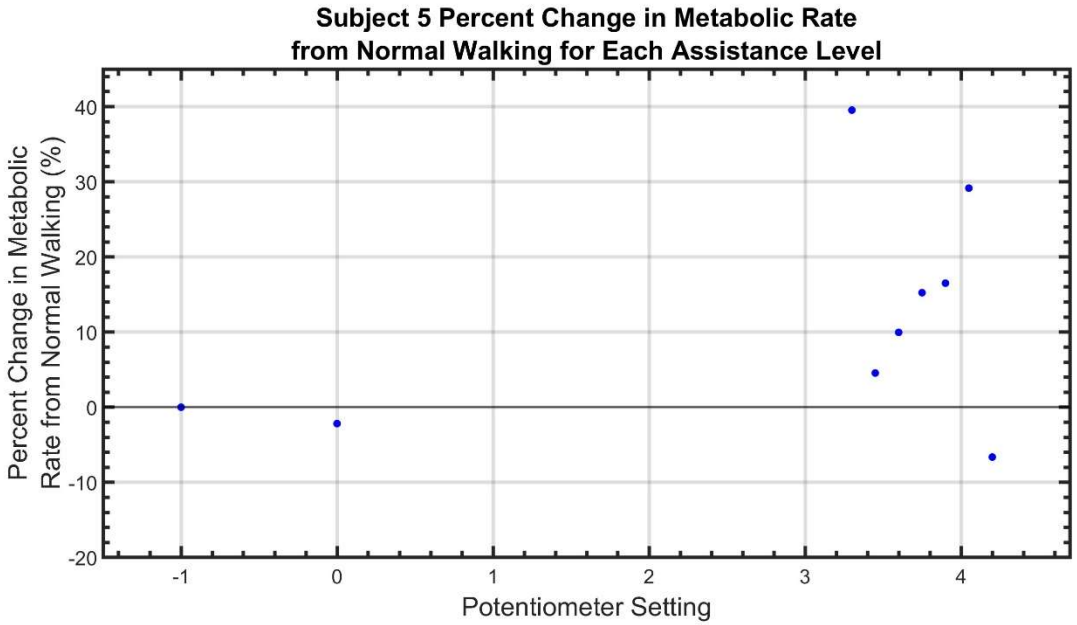


Figure 38. Subject 5's percent change in metabolic rate from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

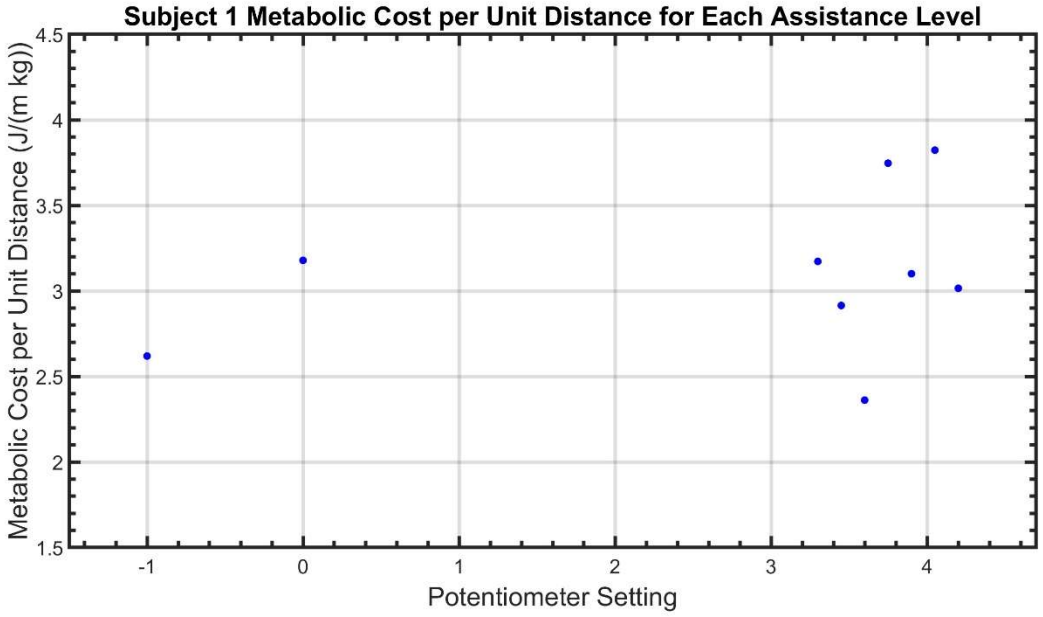


Figure 39. Subject 1's metabolic cost per unit distance for each assistance level.

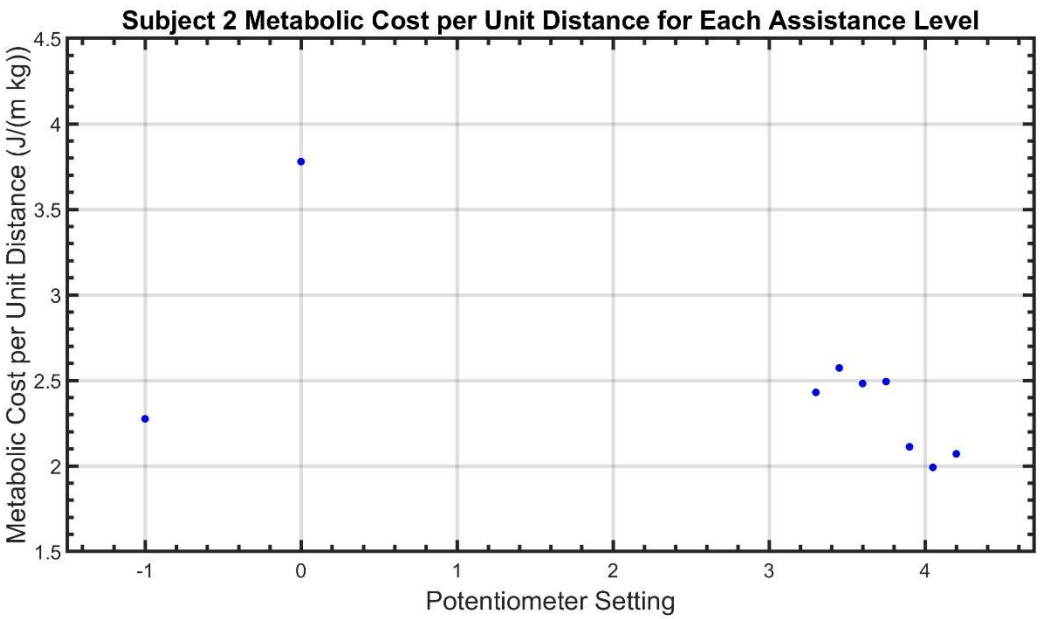


Figure 40. Subject 2's metabolic cost per unit distance for each assistance level.

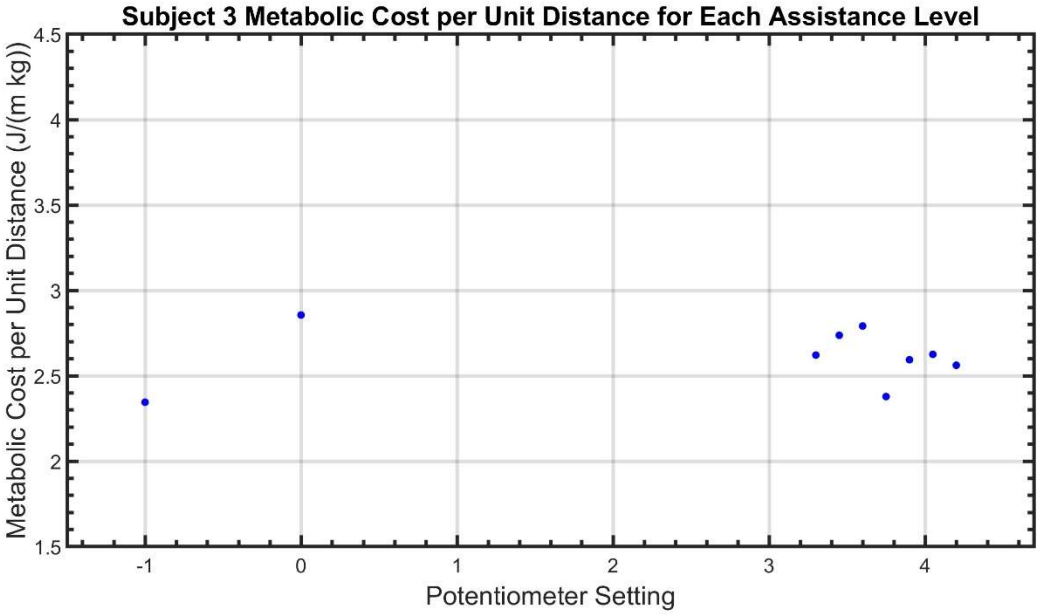


Figure 41. Subject 3's metabolic cost per unit distance for each assistance level.

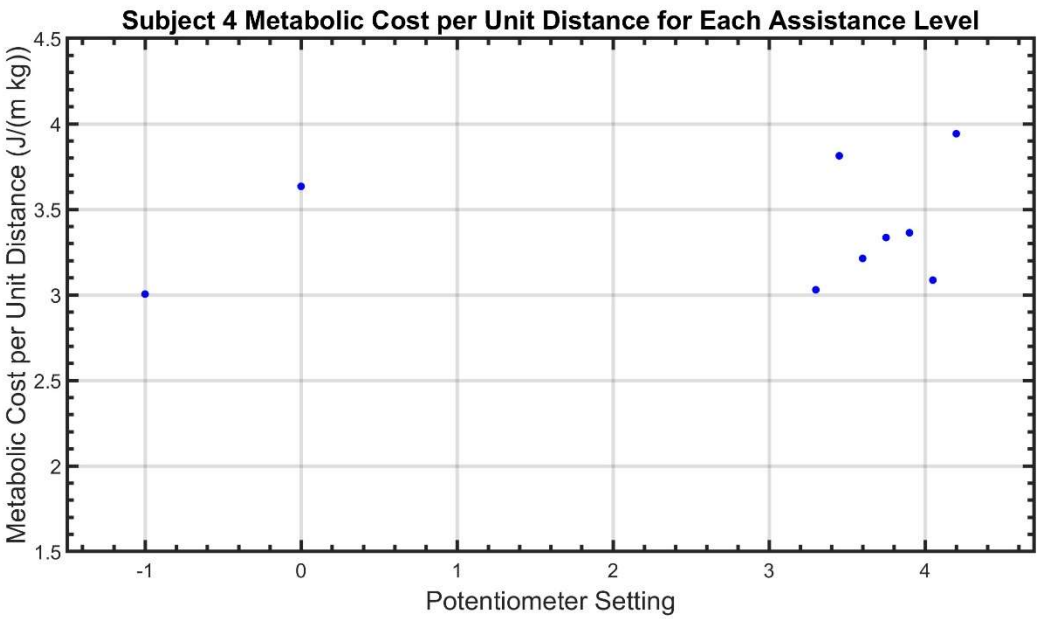


Figure 42. Subject 4's metabolic cost per unit distance for each assistance level.

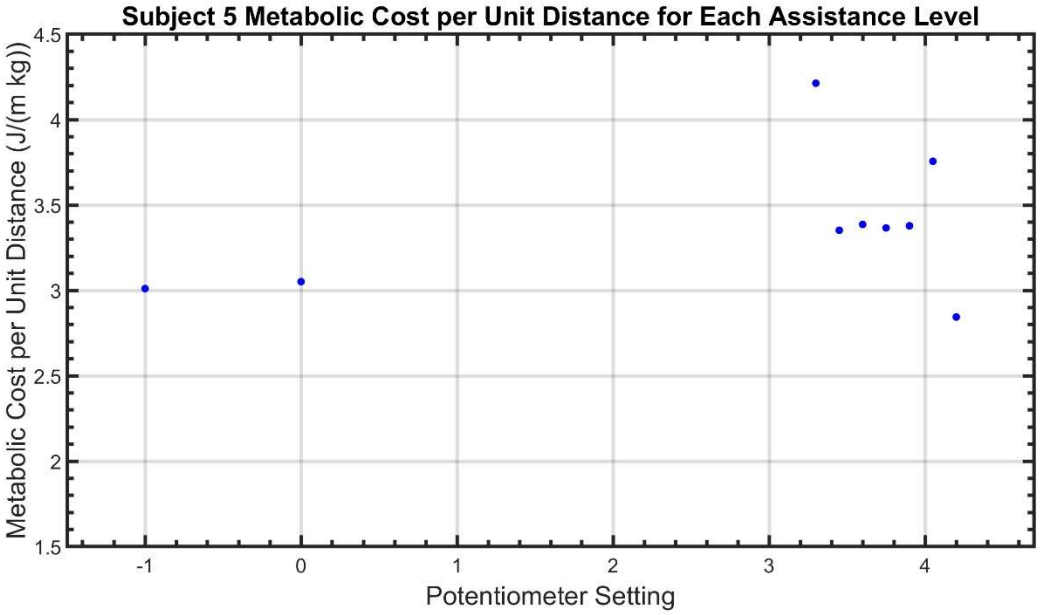


Figure 43. Subject 5's metabolic cost per unit distance for each assistance level.

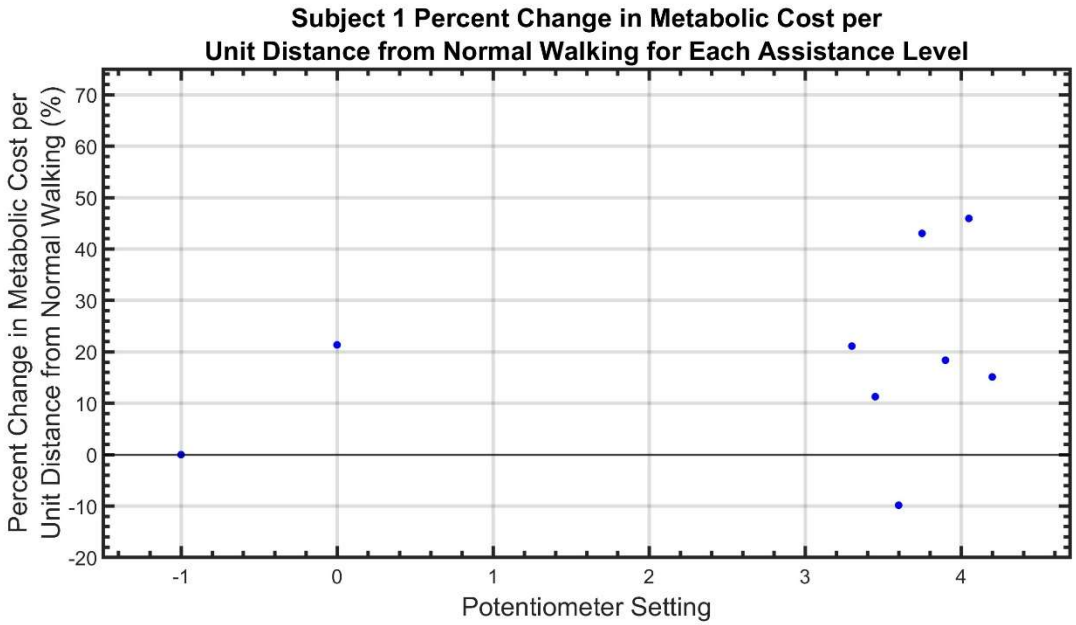


Figure 44. Subject 1's percent change in metabolic cost per unit distance from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

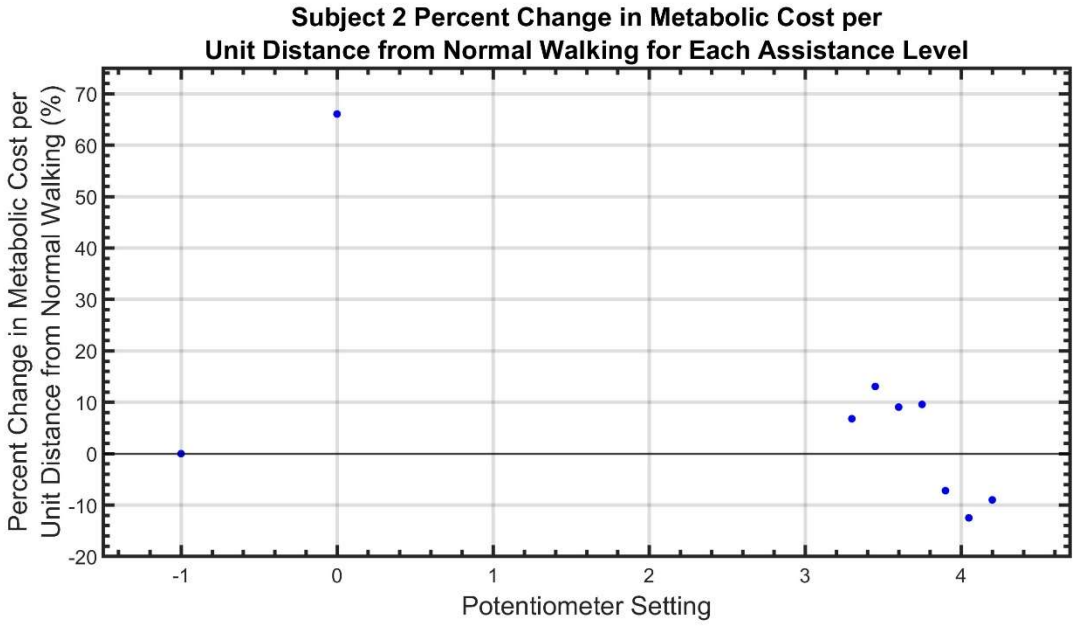


Figure 45. Subject 2's percent change in metabolic cost per unit distance from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

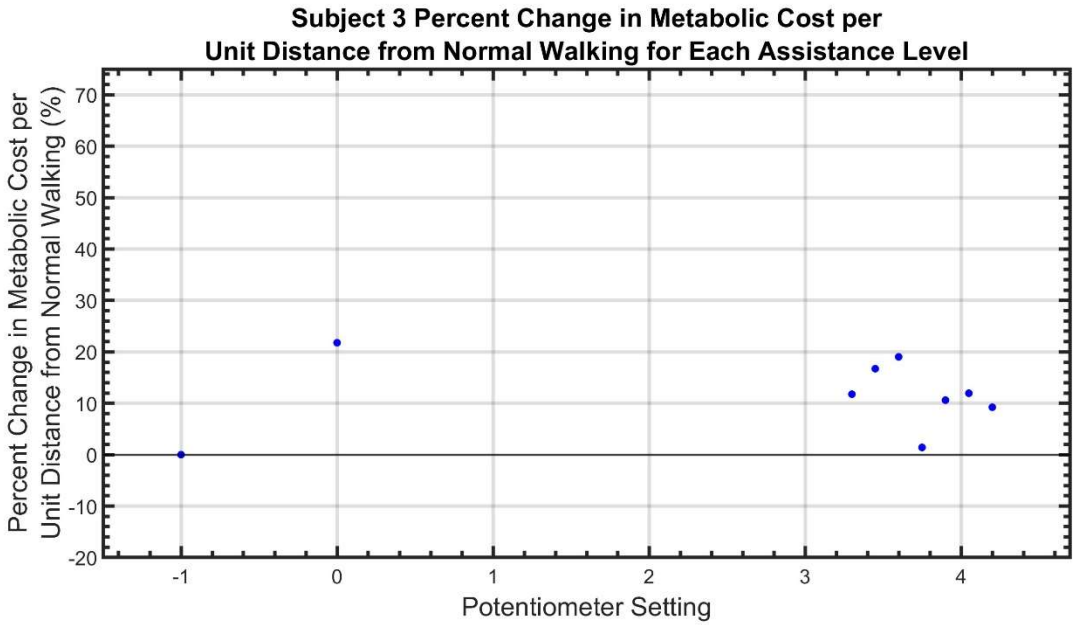


Figure 46. Subject 3's percent change in metabolic cost per unit distance from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

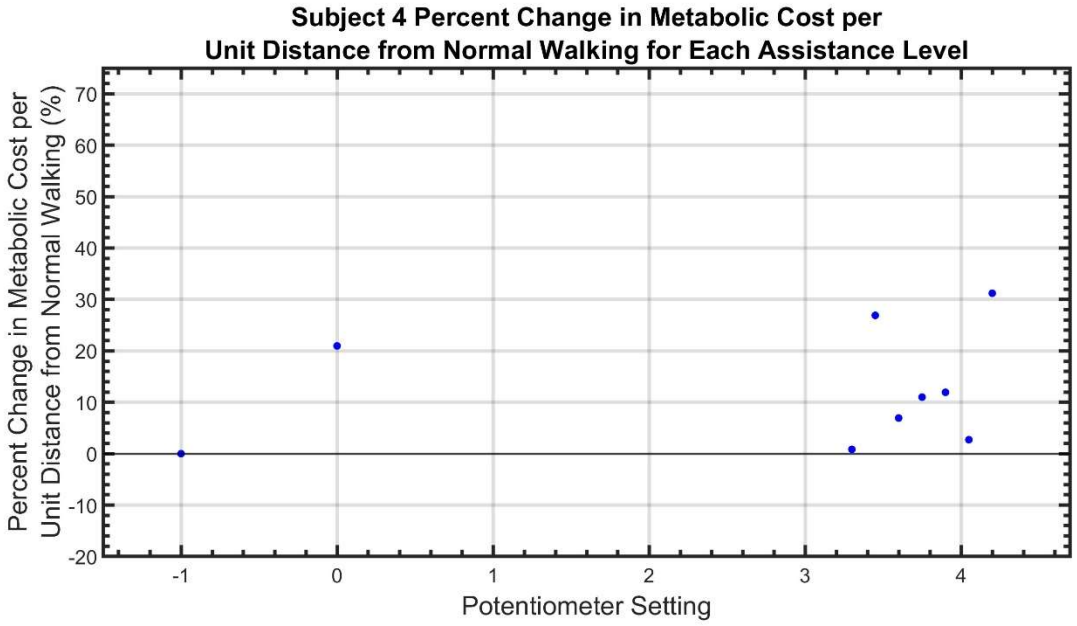


Figure 47. Subject 4's percent change in metabolic cost per unit distance from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.

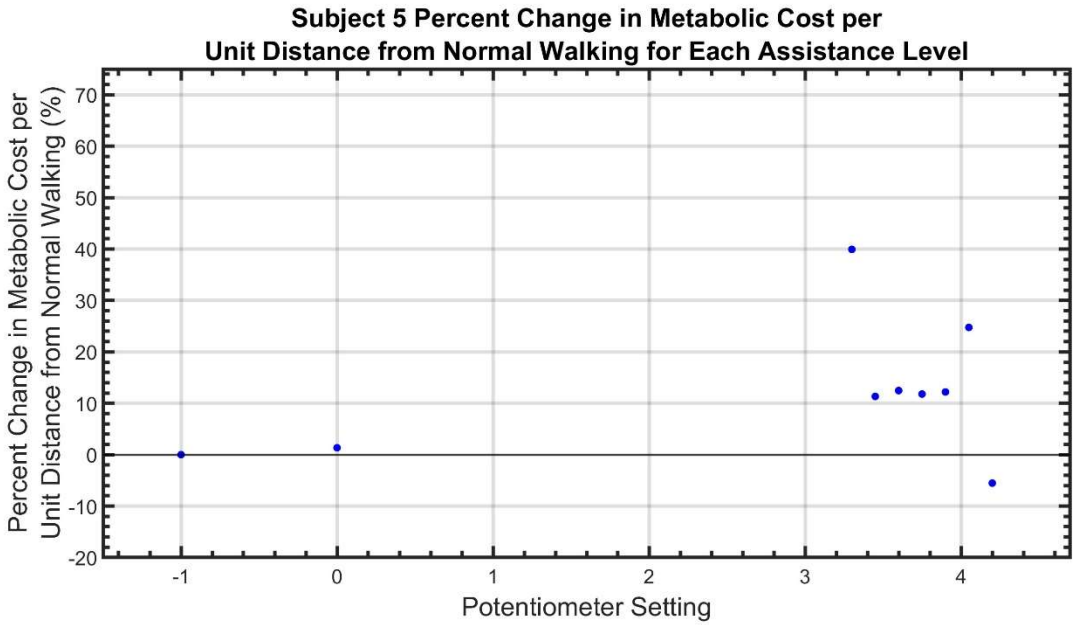


Figure 48. Subject 5's percent change in metabolic cost per unit distance from normal walking for each assistance level. The no cart trial corresponded to zero percent change because this trial was used as the reference value for calculating percent change.