Eur J Appl Physiol (2016) 116:1565–1573
DOI 10.1007/s00421-016-3408-9

ORIGINAL ARTICLE

# Pedelecs as a physically active transportation mode

**James E. Peterman**[1] · **Kalee L. Morris**[1] · **Rodger Kram**[1] · **William C. Byrnes**[1]

Received: 4 April 2016 / Accepted: 31 May 2016 / Published online: 14 June 2016

**Abstract**

*Introduction* Pedelecs are bicycles that provide electric assistance only when a rider is pedaling and have become increasingly popular.

*Purpose* Our purpose was to quantify usage patterns over 4 weeks of real-world commuting with a pedelec and to determine if pedelec use would improve cardiometabolic risk factors.

*Methods* Twenty sedentary commuters visited the laboratory for baseline physiological measurements [body composition, maximum oxygen consumption ($\dot{V}O_2$max), mean arterial blood pressure (MAP), blood lipid profile, and 2-h oral glucose tolerance test (OGTT)]. The following 4 weeks, participants were instructed to commute using a pedelec at least 3 days week$^{-1}$ for 40 min day$^{-1}$ while wearing a heart rate monitor and a GPS device. Metabolic equivalents (METS) were estimated from heart rate data. Following the intervention, we repeated the physiological measurements.

*Results* Average total distance and time were 317.9 ± 113.8 km and 15.9 ± 3.4 h, respectively. Participants averaged 4.9 ± 1.2 METS when riding. Four weeks of pedelec commuting significantly improved 2-h post-OGTT glucose (5.53 ± 1.18–5.03 ± 0.91 mmol L$^{-1}$, $p < 0.05$), $\dot{V}O_2$max (2.21 ± 0.48–2.39 ± 0.52 L min$^{-1}$, $p < 0.05$), and end of $\dot{V}O_2$max test power output (165.1 ± 37.1–189.3 ± 38.2 W, $p < 0.05$). There were trends for improvements in MAP (84.6 ± 10.5–83.2 ± 9.4 mmHg, $p = 0.15$) and fat mass (28.6 ± 11.3–28.2 ± 11.4 kg, $p = 0.07$).

*Conclusion* Participants rode a pedelec in the real world at a self-selected moderate intensity, which helped them meet physical activity recommendations. Pedelec commuting also resulted in significant improvements in 2-h post-OGTT glucose, $\dot{V}O_2$max, and power output. Pedelecs are an effective form of active transportation that can improve some cardiometabolic risk factors within only 4 weeks.

**Keywords** Electric assist bicycle · Intervention · Transportation · Cycling · Active commuting

**Abbreviations**

| | |
|---|---|
| BMI | Body mass index |
| DXA | Dual energy X-ray absorptiometry |
| GXT | Graded exercise test |
| HDL | High-density lipoprotein |
| HOMA | Homeostasis model assessment |
| LDL | Low-density lipoprotein |
| MAP | Mean arterial blood pressure |
| METS | Metabolic equivalents |
| OGTT | Oral glucose tolerance test |
| RPE | Rating of perceived exertion |
| $\dot{V}O_2$max | Maximum oxygen consumption |
| WHO | World Health Organization |

## Introduction

Electric bicycles are a novel mode of transportation that has become increasingly popular. In China, from 2000 to 2012, the annual sales soared from 300,000 to 30 million (Statista 2016). In Holland, the sales grew by 30 % in the

---

Communicated by Jean-René Lacour.

✉ James E. Peterman
james.peterman@colorado.edu

[1] Department of Integrative Physiology, UCB 354, University of Colorado Boulder, Boulder, CO 80309, USA

year 2015 (Bike Europe 2016b). This rapid increase in sales seen throughout Asia and Europe is also anticipated in the USA (Bike Europe 2016a). “Pedelecs” are one type of bicycle in the broader category of electric bicycles. Pedelecs provide modest electric motor assistance only when the rider is actively pedaling. With a pedelec, a rider is required to pedal, but they are able to travel at faster speeds and are less likely to be limited by possible aerobic fitness constraints. Because pedaling is required, it has been suggested that pedelecs could be used to effectively promote active commuting (de Geus et al. 2013; Gojanovic et al. 2011; Louis et al. 2012) and help individuals meet the physical activity recommendations (150 min week$^{-1}$ of moderate intensity or 75 min week$^{-1}$ of vigorous intensity physical activity) from organizations like the World Health Organization (WHO 2010).

The commute to work provides an ideal opportunity for an intervention that promotes physical activity. In many developed countries, a significant amount of time is spent sitting while driving to the workplace. For example, roughly 86 % of Americans commute to work by car with the average commute to work being 25.1 min one way (McKenzie 2013). A large number of workers have longer commutes with 8.1 % commuting at least 60 min (McKenzie and Rapino 2011). Sitting in the car for these extended bouts is associated with a variety of negative health outcomes. For example, with every additional hour spent in the car, there is a 6 % increase in likelihood of obesity (Frank et al. 2004). Additionally, commuting distance, which is related to the time spent in the car, was found to be associated with adverse changes in cardiorespiratory fitness, adiposity, and other metabolic risk factors (Hoehner et al. 2012).

There are a variety of physically active alternatives to commuting by car that could improve cardiometabolic risk factors. For example, every additional kilometer walked per day is associated with a 4.8 % reduction in the likelihood of obesity (Frank et al. 2004). However, common commuting distances preclude walking. A traditional bicycle can be faster than walking, but distance and terrain (i.e., hills) can still be limiting due to fitness constraints and the physical effort can lead to work hygiene concerns. Pedelecs are a potentially better mode of active transportation, because they can overcome many of the deterrents associated with physically active commuting.

Despite receiving assistance from a motor, riding a pedelec still requires active pedaling, which may help improve cardiometabolic risk factors. For example, de Geus et al. (2013) found improvements in maximum power output during an exercise test following 6 weeks of pedelec commuting. Furthermore, acute bouts of pedelec riding elicit an increase in metabolic equivalents (METS) that is comparable to performing moderate-intensity physical activity (Gojanovic et al. 2011; Louis et al. 2012; Sperlich et al. 2012), which is recommended for improving cardiometabolic risk factors (WHO 2010). Even if a moderate intensity is not reached, riding a pedelec could still improve risk factors. Previous research has shown that even light-intensity physical activity can mitigate risk factors like elevated blood glucose levels during an oral glucose tolerance test (OGTT) (Dunstan et al. 2012). Based on the average one-way American driving commute to work (25.1 min) and assuming that commuting by pedelec will take the same amount of time, replacing the car with riding a pedelec represents an additional 50 min per day that an individual could be performing physical activity. Thus, to meet the recommendations for physical activity, round-trip commuting by pedelec would only need to be done three times per week.

Previous research has suggested pedelec commuting can be used to meet physical activity recommendations; however, actual real-world usage patterns of pedelecs remain unknown. Thus, the purpose of this study was to track self-selected pedelec usage patterns of participants in the real world. Additionally, we examined how commuting with a pedelec for 4 weeks might influence cardiometabolic risk factors. We hypothesized that replacing a car/public transport commute with riding a pedelec would result in improvements in plasma glucose concentration following an OGTT, lipid profile, blood pressure, physical fitness, and body composition.

## Methods

Twenty-one sedentary commuters who did not perform regular exercise participated. However, one participant was unable to follow the study requirements and was not included in data analysis resulting in a total of 20 who completed the protocol (14 females, 6 males). The average age was 41.5 ± 11.5 years with a range of 22–55 years. A preliminary questionnaire administered via REDCap online software was used to screen potential participants. Participants were included if they participated in planned exercise less than 150 min week$^{-1}$ and if they self-reported that their job did not require significant physical activity. Additionally, participants were considered sedentary commuters only if their commute to work involved sitting in a car and/or public transit. Descriptive data for our participants are given in Table 1. All participants were informed of the risks involved in the study and gave written informed consent before participating. The experimental protocol for this study was approved by the University of Colorado Boulder Institutional Review Board.

**Table 1** Cardiometabolic variables (mean ± SD) for participants pre- and post-pedelec intervention ($n = 20$)

| | Pre | Post |
|---|---|---|
| Height (m) | 1.71 ± 0.10 | 1.71 ± 0.10 |
| Mass (kg) | 79.0 ± 16.7 | 78.6 ± 16.8 |
| BMI (kg $m^{-2}$) | 26.8 ± 4.9 | 26.7 ± 5.0 |
| Lean mass (kg) | 47.3 ± 7.5 | 47.4 ± 7.4 |
| Fat mass (kg) | 28.6 ± 11.3 | 28.2 ± 11.4 |
| $\dot{V}O_2$max (L $min^{-1}$) | 2.21 ± 0.48 | 2.39 ± 0.52* |
| End of GXT power (W) | 165.1 ± 37.1 | 189.3 ± 38.2* |
| Mean arterial pressure blood pressure (mmHg) | 84.6 ± 10.5 | 83.2 ± 9.4 |
| Systolic blood pressure (mmHg) | 110.0 ± 12.4 | 109.1 ± 10.9 |
| Diastolic blood pressure (mmHg) | 67.7 ± 8.8 | 67.0 ± 8.0 |
| Total cholesterol (mmol $L^{-1}$) | 3.90 ± 0.87 | 3.92 ± 0.79 |
| LDL (mmol $L^{-1}$) | 2.33 ± 0.80 | 2.34 ± 0.71 |
| HDL (mmol $L^{-1}$) | 1.21 ± 0.24 | 1.18 ± 0.22 |
| Triglycerides (mmol $L^{-1}$) | 0.95 ± 0.42 | 0.91 ± 0.27 |
| Fasting plasma glucose (mmol $L^{-1}$) | 4.99 ± 0.52 | 5.02 ± 0.47 |
| 2-h post-plasma glucose (mmol $L^{-1}$) | 5.53 ± 1.18 | 5.03 ± 0.91* |
| HOMA | 2.46 ± 0.95 | 2.55 ± 0.82 |
| Sedentary time (min $day^{-1}$) | 512.9 ± 79.6 | 544.8 ± 90.0 |
| Moderate to vigorous physical activity (min $day^{-1}$) | 28.1 ± 17.5 | 29.0 ± 20.2 |
| Moderate to vigorous physical activity accumulated in bouts >10 min (min $day^{-1}$) | 11.7 ± 14.3 | 13.0 ± 15.2 |
| Step count (steps $day^{-1}$) | 7560 ± 2328 | 7593 ± 2241 |
| Activity monitor wear time (h $day^{-1}$) | 13.7 ± 1.0 | 14.4 ± 1.3* |

* Significant difference between pre- and post-pedelec intervention ($p < 0.05$)

## Preliminary physiological testing

All study visits occurred at the University of Colorado Boulder Clinical Translational Research Center. The first visit determined if participants were healthy enough to participate. Participants met with a physician for a brief medical history, physical examination, and a blood draw to confirm they were not diabetic and did not have high cholesterol (indicated by fasting glucose levels <7 mmol $L^{-1}$ and fasting total cholesterol levels <6.18 mmol $L^{-1}$). Following this, participants had a whole body dual energy X-ray absorptiometry (DXA) scan (GE LUNAR DXA system, Little Chalfont, UK). Participants then met with a nutritionist who instructed them on how to record and follow a prescribed diet for the 3 days leading up to the OGTT performed during visits 3 and 4.

Participants then performed a graded exercise test (GXT) on a cycling ergometer (Lode Excalibur Sport, Groningen, The Netherlands). The initial stage of the GXT was a workload of 0 W and increased every 3 min by 25 W (for females) or 40 W (for males) until they reached a 15 on the Borg Rating of Perceived Exertion (RPE) scale. After reaching an RPE of 15, stages became 2 min long and continued until volitional fatigue was reached. During the GXT, respiratory gas exchange and energy expenditure were measured using a ParvoMedics TrueOne 2400 computerized indirect calorimetry system (Sandy, UT, USA). Heart rate was measured using radio telemetry (Polar®, Kempele, Finland) that was synced with the ParvoMedics calorimetry system.

Calibration of the indirect calorimetry system occurred prior to the GXT. Gas fractions were calibrated with a primary standard gas mixture within the physiological range (15.99 % $O_2$ and 4.01 % $CO_2$). The volume was calibrated using a 3 L syringe at five distinct flow rates within the expected range of the study protocol. Calibration was considered to be complete when recorded volumes were within 3 % of the calibration volumes, and gas fractions were within 0.2 % of calibration values (e.g., 15.99 ± 0.02 %). Respiratory and heart rate measurements were averaged every 15 s. Data from the ParvoMedics metabolic cart were downloaded as Microsoft Excel (Redmond, Washington) files and data from the last minute of each 3-m submax stage were averaged. Maximum oxygen consumption ($\dot{V}O_2$max) and maximum heart rate were determined as the highest 30-s average during the GXT.

It has been suggested that there may be a learning curve associated with performing a GXT such that the second

GXT produces greater values (higher $\dot{V}O_2$max and higher mechanical peak power output) (Roca et al. 1992). Therefore, to minimize this potential confounder, at least 2 days after visit 1, participants reported back to the laboratory to repeat the GXT. No differences in common markers of performance (i.e., $\dot{V}O_2$max) were found between the GXTs performed on visit 1 and visit 2, so the average from these two visits was used as the pre-pedelec intervention value. Three participants did not perform a second pre-intervention GXT and one participant was unable to provide a maximal effort for their second GXT. As a result, for these four individuals, the values from their GXT performed on visit 1 were used as the pre-intervention data.

To determine if commuting with a pedelec results in compensatory changes to daily physical activity levels as some interventions have shown (Mansoubi et al. 2015), participants wore an activity monitor (Actigraph GT3x+, Actigraph, Pensacola, FL) prior to and during the intervention. Because the Actigraph activity monitor does not accurately detect cycling, the activity data collected were used to estimate only non-cycling physical activity. However, to improve wear compliance, participants were still instructed to wear the monitor at all times even when cycling during the intervention. Baseline, pre-intervention data were collected for the 7 days following the second GXT. Physical activity levels during the intervention were again measured during the final week of the 4-week intervention. The activity monitor was worn on the right hip and data were recorded in 1-min epochs with physical activity intensity divided into two categories: sedentary ($<100$ counts min$^{-1}$) and moderate to vigorous intensity ($>1952$ counts min$^{-1}$) (Freedson et al. 1998). The activity monitor had to be worn for $\geq 10$ h day$^{-1}$ to be considered a valid wear day. In addition, to prepare for the OGTT, dietary restrictions were placed on participants for the 3 days prior to visit 3. Participants were instructed to eat at least 150 g of carbohydrate each of the 3 days and refrain from caffeine or alcohol consumption. On the day of visit 3, participants arrived at the laboratory following an overnight fast and traveled by car to the laboratory to minimize physical activity.

Upon arrival at the laboratory for visit 3, resting blood pressure was determined using an automatic blood pressure cuff (GE Dinamap, Little Chalfont, UK) placed on the right arm. Participants sat alone in a quiet room with feet flat on the floor while measurements were taken every 3 min until values stabilized to ±5 mmHg. Following this, two blood samples were taken via a single venipuncture: 5 mL for determining a blood lipid profile [low-density lipoprotein (LDL), high-density lipoprotein (HDL), triglycerides, and total cholesterol] and 2 mL to determine resting, fasting plasma glucose and insulin levels. Following the collection of blood, participants performed the OGTT. Participants had 2 min to consume a 296 mL beverage containing 75 g of glucose (Azer Scientific, Morgantown, PA, USA). For 2 h following the consumption of the glucose drink, participants sat quietly and then had another venipuncture to determine the 2-h post-plasma glucose levels. Collected blood samples were spun at 3700 RPM for 10 min to separate the plasma. From the plasma, duplicate samples were drawn for the determination of plasma glucose. For each duplicate, 25 μL of plasma was mixed with a "cocktail" containing 50 μL of a buffer, lysing agent (Triton XL-100), and anti-glycolytic (sodium fluoride) solution. Each duplicate sample was then analyzed using a YSI 2300 glucose analyzer (YSI, Yellow Springs, OH, USA). Plasma insulin levels were determined using a competitive radioimmunoassay kit (Millipore Corporation, Billerica, MA, USA). In addition, insulin sensitivity was determined using the homeostasis model assessment (HOMA) (Matthews et al. 1985). The HOMA is an estimate of insulin sensitivity using fasting plasma glucose and insulin levels with lower values indicating improved insulin sensitivity.

## Pedelec intervention

Following the three visits that made up the preliminary physiological testing, participants were provided with a pedelec. Two different pedelecs were used: a 2015 Trek T80+ (Waterloo, WI, USA) and a 2013 E-Motion City Wave (Foothill Ranch, CA, USA). The Trek had a motor located in the rear wheel hub and the E-Motion had a mid-drive motor, which provided power to the bicycle crank. Both pedelecs had 250 W motors that required pedaling to get any assistance and only provided assistance up to speeds of 32.2 km h$^{-1}$. Thirteen participants rode a Trek, six rode an E-Motion bicycle, and one rode an E-Motion for 2 weeks followed by a Trek for 2 weeks because of technical difficulties. Participants were instructed to commute using their pedelec for 4 weeks, a minimum of 3 days per week. For each of those 3 days, participants were asked to ride at least a total of 40 min, which could be split up or done at one time. Additionally, participants were free to ride the pedelec as much as they liked for additional work commutes, pleasure, errands, etc.

While riding the pedelec, participants wore a heart rate monitor chest strap (PowerTap, Madison, WI) that was linked to a GPS device (Garmin Edge 500 or Edge 510, Olathe, KS). The heart rate data were used to estimate the energy expenditure and METS participants rode their pedelec during the intervention. A member of the research team met with each participant once a week to download data from the GPS using PowerAgent software (PowerTap, Madison, WI). During this weekly meeting, participants were asked to give feedback about their experience using the pedelec and their responses were recorded. On the final week of the 4-week intervention, participants wore an activity monitor as they had prior to the intervention.

### Post-physiological testing

An average of 4.4 weeks after starting the pedelec intervention, participants reported back to the laboratory for visit 4. For the 3 days prior to visit 4, participants were instructed to repeat the same diet as they had for visit 3. Again, participants were instructed to arrive following an overnight fast and to travel to the laboratory via automobile. Visit 4 had the same format as visit 3 with participants having blood pressure measured followed by a blood draw for a blood lipid profile and an OGTT. At least 2 days following visit 4 (an average of 5 weeks after starting the pedelec intervention), participants reported to the laboratory for visit 5. During the time between visits 4 and 5, participants were instructed to continue using their pedelec as they had the previous weeks. Visit 5 involved a DXA scan and GXT. The GXT stages during visit 5 were matched to what the participants performed during visit 2 with participants again instructed to exercise until volitional fatigue.

### Analysis

Although there were no problems with the GPS data (i.e., ride distance and time), there were some cases in which heart rate data were missing for part or all of a ride. In these cases, various attempts were made to prorate the heart rate data. If less than 25 % of heart rate data were missing from a single ride, the average (without zeroes) was taken for that ride. If more than 25 % of heart rate data were missing, the average heart rate for similar rides was substituted. When heart rate data were missing and rides were not the typical commuting route, no average heart rate for the particular ride was entered (5.5 % of rides for those individuals included in the analysis). Six participants had more than 25 % of their rides missing heart rate data, so their heart rate, METS, and energy expenditure data were not included in the analysis. One of these six participants rode a stationary exercise bike for more than 25 % of the intervention to mimic the pedelec intervention due to other life obligations. As a result, limited GPS data were collected, and for this individual only cycling time was recorded.

Energy expenditure and METS were estimated from individual regression equations using the participant's data from the submax 3 min stages of the GXT. A significant difference between the two pre-intervention GXTs was found for the slope of the power vs. heart rate regression possibly due to visit 1 nervousness, which elevated heart rate. Thus, the regression equations determined from the visit 2 GXT were used for estimating METS and energy expenditure. The individual regression equations for the prediction of energy expenditure and METS while riding the pedelec were calculated using Microsoft Excel. Pre- and post-intervention variables were compared using dependent two-tail *t* tests conducted using the SPSS software (SPSS Inc. version 22, Chicago, IL). Statistical significance was designated at the $p < 0.05$ level. Data are presented throughout the paper as mean ± SD.

## Results

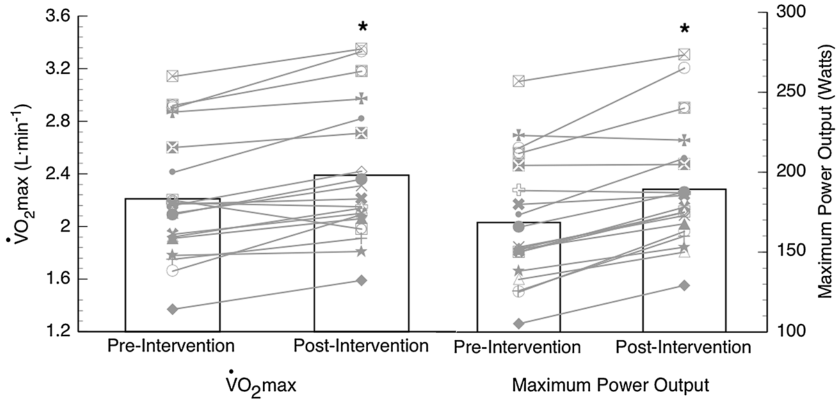
Pedelec usage data are presented in Table 2. Participants rode at an average speed of 20.1 ± 3.8 km $h^{-1}$ and a self-selected intensity of 72.1 ± 5.4 % of their maximum heart rate. Based on this intensity, the average estimated energy expenditure while riding was 6.5 ± 1.9 kcal $min^{-1}$ and the average METS was 4.9 ± 1.2 METS. The average daily ride distance was 19.7 ± 8.8 km with daily ride time averaging 58.5 ± 15.2 min. The average daily pedelec MET h was 5.2 ± 2.1 MET h and the average daily cycling metabolic energy expenditure was 420.1 ± 221.8 kcal. Weekly pedelec ride time, MET h, and metabolic energy expenditure averaged 205.0 ± 43.3 min, 17.4 ± 6.0 MET h, and 1396.9 ± 634.4 kcal, respectively. The average total distance cycled was 317.9 ± 113.8 km (range 135.9–566.0 km). Total pedelec cycling time was 15.9 ± 3.4 h (range 9.8–22.2 h). Additionally, no significant difference was found between distances cycled during the first

**Table 2** Mean ± SD of pedelec riding data in different time epochs

| | Per ride | Cycling days | Weekly | Total |
|---|---|---|---|---|
| Time (min) | 33.1 ± 14.5 | 58.5 ± 15.2 | 205 ± 43.3 | 954.8 ± 202.6 |
| Distance (km) | 11.2 ± 6.8 | 19.7 ± 8.8 | 69.4 ± 24.4 | 317.9 ± 113.8 |
| Energy expenditure (kcal) | 244.1 ± 171.0 | 420.1 ± 221.8 | 1396.9 ± 634.4 | 6441.5 ± 2863.4 |
| MET h | 2.7 ± 0.3 | 5.2 ± 2.1 | 17.4 ± 6.0 | 79.9 ± 26.4 |

The variable time includes $n = 20$, distance includes $n = 19$, and energy expenditure and MET h includes $n = 14$

**Fig. 1** Aerobic fitness measurements pre- and post-intervention. Only 4 weeks of commuting with a pedelec significantly increased $\dot{V}O_2$max and maximum power at the end of the GXT

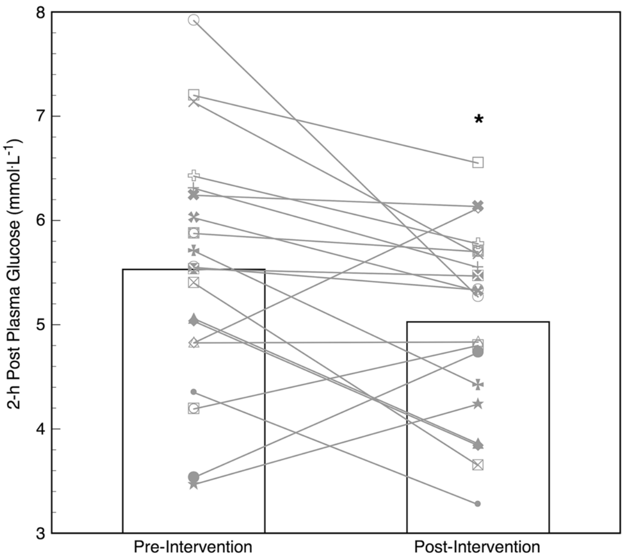


* Significant difference between pre- and post-intervention (p<0.05)

week (71.1 ± 24.4 km) compared to the fourth week (62.6 ± 32.8 km). All participants exceeded the minimum riding requirements with 11 of the 20 participants riding at least 50 % more than required.

Non-cycling physical activity remained constant despite the pedelec intervention (Table 1). Time spent sedentary before and during the intervention was 512.9 ± 79.6 and 544.8 ± 90.0 min day$^{-1}$, respectively. Moderate to vigorous physical activity time was 28.1 ± 17.5 and 29.0 ± 20.2 min day$^{-1}$ for before and during the intervention, respectively. A significant difference was found for daily activity monitor wear time between the before and during time periods (13.7 ± 1.0 and 14.4 ± 1.3 h day$^{-1}$, $p < 0.05$). Taking this into consideration, sedentary time as a percent of daily wear time was 62.1 and 62.8 %, while moderate to vigorous physical activity was 3.5 and 3.4 % for before and during, respectively. While the activity monitor data suggests participants were meeting the recommendations for total time of physical activity, the majority of activity bouts were not performed for at least 10 min which is what the WHO recommends. When including only bouts that were at least 10 min in duration, average moderate to vigorous physical activity time was 11.7 ± 14.3 and 13.0 ± 15.2 min day$^{-1}$ for before and during the intervention, respectively.

Following the 4-week pedelec intervention, significant improvements were found in 2-h post-OGTT glucose (5.53 ± 1.18–5.03 ± 0.91 mmol L$^{-1}$, $p < 0.05$), $\dot{V}O_2$max (2.21 ± 0.48–2.39 ± 0.52 L min$^{-1}$, $p < 0.05$), and power output achieved at the end of the GXT (165.1 ± 37.1–189.3 ± 38.2 W, $p < 0.05$) (Figs. 1, 2). In addition, there were trends for improvements in mean arterial blood pressure (MAP) (84.6 ± 10.5–83.2 ± 9.4 mmHg, $p = 0.15$) and fat mass (28.6 ± 11.3–28.2 ± 11.4 kg, $p = 0.07$). No significant changes were found in the other glucose measures, blood lipid profile, or body composition measures (Table 1).



* Significant difference between pre- and post-intervention (p<0.05)

**Fig. 2** Two-hour post-plasma glucose levels were significantly lower following 4 weeks of pedelec commuting

## Discussion

Despite the electric assistance, participants self-selected to ride the pedelecs at a moderate intensity. This self-selected riding intensity helped them meet the recommendations for physical activity as established by organizations like the WHO. Furthermore, in agreement with our hypothesis, we found commuting with a pedelec for 4 weeks significantly improved some cardiometabolic risk factors. Two-hour post-OGTT glucose was lower and both $\dot{V}O_2$max and power output at the end of the GXT were higher following the pedelec intervention. Additionally, there were trends for the pedelec intervention to decrease MAP and fat mass.

Previous research in which participants acutely rode a pedelec found participants rode at a moderate intensity

(Gojanovic et al. 2011; Louis et al. 2012; Sperlich et al. 2012) and the present study extends these findings to the real world. The average intensity while riding a pedelec was 4.9 METS, which is within the range suggested for cardiorespiratory benefits. The average MET h $\text{week}^{-1}$ participants obtained (17.4 MET h $\text{week}^{-1}$) also exceeds the recommendations for physical activity by organizations like the WHO (2010). Furthermore, the average duration of individual cycling bouts was greater than 10 min which is another requirement for meeting the WHO recommendations. Thus, the decrease in 2-h post-glucose and the increase in the fitness level of participants should not be surprising. Moreover, even if participants chose to ride at a lower intensity, it is possible that 2-h post-glucose levels would still decrease as previous research has shown with light-intensity walking (Dunstan et al. 2012). Therefore, the pedelec design which requires pedaling to get any electric assistance makes it an effective tool to improve cardiometabolic risk factors.

There are a variety of deterrents associated with active commuting such as long distances and difficult hills, but a pedelec's modest electric assistance helps to reduce these concerns. Additionally, commuting with a pedelec can help individuals incorporate physical activity into their day without requiring them to set aside time specifically for exercise and thus limit some of the barriers associated with meeting the physical activity recommendations (Mayo Clinic 2016). It is possible that the minimum riding requirement for the study influenced the real-world pedelec usage patterns. However, we note that all participants rode more than the minimum requirements with over half the participants riding at least 50 % more than the required amount. Furthermore, there was no significant difference in cycling distance between the first and fourth week of the pedelec intervention, suggesting there was no loss of interest in riding the pedelec. These findings suggest the data collected represents the true real-world usage patterns. Also, throughout the meetings during the intervention, participants repeatedly remarked on how fun and easy the pedelecs were to ride and how they were able to easily incorporate them into their everyday lives. This fun and ease suggests pedelecs could be a sustainable intervention to promote active commuting. While we did not record the purpose of participant's pedelec trips, many remarked how they had begun to substitute riding the pedelec for driving their car for regular errands. After completing the study, two participants purchased their own electric assist bicycle and others stated they began riding their traditional bicycle more. This fun and easier perceived effort associated with riding a pedelec may especially help older individuals remain active.

Activity monitor data did not detect any compensatory changes in non-cycling physical activity as a result of pedelec commuting. Step count, sedentary time, and moderate to vigorous physical activity levels were similar before the pedelec intervention and during the intervention. Based on the intensity with which participants rode the pedelec, the intervention would be expected to increase physical activity levels; however, Actigraph activity monitors do not accurately detect cycling. To improve wear time compliance, participants were still instructed to wear the activity monitor when cycling. The activity monitors detect movement when cycling and previous research has found that this movement results in an average of 1157 ± 974 counts $\text{min}^{-1}$ (Herman Hansen et al. 2014). This count is below the moderate- to vigorous-intensity cutoff we used and may explain why no differences were found during the pedelec intervention. Thus, this data suggests that participants continued their normal activity levels when not riding the pedelec and did not use the pedelec to replace other physical activity. This is an important consideration because other interventions like standing desks have been shown to result in compensatory reductions in other physical activity (Mansoubi et al. 2015).

Pedelec commuting also influenced some cardiometabolic risk factors. No previous pedelec and traditional active commuting studies have examined the potential for changes in blood glucose regulation. However, 2-h post-plasma glucose levels are an important risk factor to measure, as they are independently associated with risk for all-cause and cardiovascular disease mortality (Saydah et al. 2001). While we found no significant difference for fasted blood glucose, we did find 2-h post-plasma glucose levels significantly decreased by 0.50 mmol $\text{L}^{-1}$. This 2-h post-time point during an OGTT is a common clinical measure of diabetes risk and even small improvements within healthy individuals like those seen in the present study are associated with decreased risk for cardiovascular disease (Levitan et al. 2004). Additionally, it has been suggested that time spent in sedentary behaviors is a risk factor for elevated blood glucose independent of physical activity levels (Healy et al. 2007). Whether the decrease in 2-h post-glucose was due to decreasing the sedentary commute time, increasing moderate to vigorous physical activity by riding the pedelec, or a combination of both should be the focus of future research.

Similar to de Geus et al. (2013), we found power output at the end of the GXT significantly increased in participants that commuted by pedelec. Unlike de Geus et al., we also found $\dot{V}\text{O}_2\text{max}$ significantly increased. While participants in our study had similar starting $\dot{V}\text{O}_2\text{max}$ values (2.21 and 2.25 L $\text{min}^{-1}$ for the present study and de Geus et al., respectively), the reason for the difference may be due to differences in weekly distance ridden (69.4 and 54.3 km $\text{week}^{-1}$ for the present study and de Geus et al., respectively). It is possible that the greater weekly riding dosage led to a greater stimulus for improvements in $\dot{V}O_2$max, as a significant correlation between $\dot{V}O_2$max and traditional cycling dosage has been shown previously (de Geus et al. 2009). It is also possible that participants rode at different intensities in the de Geus et al. study, although data were not collected on this variable. Other commuting studies (de Geus et al. 2009; Hendriksen et al. 2000) using traditional bicycles have found improvements in maximal power output and $\dot{V}O_2$max similar to ours, suggesting pedelecs can improve cardiometabolic risk factors to a similar extent as traditional bicycles.

In agreement with other commuting studies using traditional bicycles (Hendriksen et al. 2000) or pedelecs (de Geus et al. 2013), we did not find a change in body mass. Body mass changes in response to exercise interventions can be highly variable (Donnelly et al. 2013) and our results were also variable with 7 participants having an increase in body mass, 1 no change, and 12 a decrease (range +3.5 to −3.6 kg). Donnelly et al. (2013) have previously shown a significant loss of body mass when exercise is performed at 400 kcal session$^{-1}$ 5 day week$^{-1}$ for a weekly energy expenditure of 2000 kcal week$^{-1}$. In our study, on days that participants rode a pedelec, the average cycling energy expenditure was 420.1 kcal. However, participants did not ride an average of 5 day week$^{-1}$, so weekly energy expenditure was only 1396.9 kcal and most participants did not meet the weekly levels of the Donnelly et al. study. Of note, the two participants in our study who did expend 2000 kcal week$^{-1}$ lost both fat mass and body mass. It is also possible the pedelec intervention duration was not long enough to find significant differences in body mass. The Donnelly et al. study was 10 months in duration and had a similar rate of change in body mass as the present study (−0.39 and −0.40 kg/month for Donnelly et al. and the present study, respectively). This similar rate would suggest a longer pedelec intervention would have led to significant loss of body mass in our participants. Even with no significant loss in body mass, though, we did find a trend for the pedelec intervention to decrease body fat mass. Body fat is associated with increased risk for insulin resistance, type 2 diabetes, metabolic syndrome (Grant and Dixit 2015), and cancer (van Kruijsdijk et al. 2009). Thus, changes in body composition without changes in body mass can still be beneficial.

We also did not find statistically significant improvements in the blood lipid profile following the pedelec intervention. Improvements in LDL cholesterol are associated with changes in body mass and/or diet (Durstine et al. 2002). We did not find a significant loss in body mass and our study did not include a diet intervention. For HDL and triglycerides, it has been suggested that a threshold of 1200 kcal week$^{-1}$ must be met to see improvements (Durstine et al. 2001). While participants met this threshold, the duration of the study may not have been long enough to elicit significant changes. It has been suggested that 12 weeks are needed to find significant improvements in HDL and triglycerides (Durstine et al. 2002). In a year-long commuting study using traditional bicycles, de Geus et al. (2008) found improvements in HDL cholesterol in the experimental group, which were only significant after 1 year. Thus, an intervention lasting longer than 4 weeks may be required to see improvements in blood lipids.

The present study did have some limitations. First, participants may have volunteered as part of a plan to change their lifestyle to a more healthy one. This greater motivation may have resulted in riding the pedelec more. The study duration may have also been too short to see significant changes in some of our measures of cardiometabolic risk factors. Additionally, although participants were instructed to ride the pedelec at the intensity they wanted, they were aware that we were recording information about their rides. This may have influenced riding behavior and may not be a true representation of pedelec riding in the real world.

Although a test/retest design was utilized to exclude the learning effect, the lack of a control group is also a limitation. Lastly, participants did not perform regular planned exercise, but still performed roughly 30 min day$^{-1}$ of moderate to vigorous physical activity. It is likely that individuals who are less active would also see improvements in cardiometabolic risk factors while at the same time, individuals exercising greater amounts may not have the same degree of change in risk factors as found in the present study.

In conclusion, participants self-selected to ride a pedelec at a moderate-intensity in the real-world despite receiving electric assistance from a motor. These usage patterns over just 4 weeks of commuting with a pedelec were associated with significant improvements in some major cardiometabolic risk factors. Furthermore, pedelec commuting did not result in compensatory changes in physical activity suggesting it can be part of an effective strategy to increase daily energy expenditure. Additional improvements to other cardiometabolic risk factors may occur with a longer intervention and should be the focus of future research.

**Acknowledgments** Funding for the study was provided by NIH Grant UL1 TR000154, NIH Grant UL1 TR001082, the City of Boulder, and Skratch Labs LLC. The authors thank the staff at the University of Colorado Boulder Clinical Translational Research Center for their assistance in collecting the data, Pete's Electric Bikes and Elevation Cycles for assistance with the pedelecs, Kevin J. Krizek for assistance in securing funding, and the participants for volunteering their time.

## Compliance with ethical standards

**Conflict of interest** The authors have no conflict of interests to declare.

## References

Bike Europe Web Site [Internet] (2016a) EU-2010: E-bikes rising star in all major markets. http://www.bike-eu.com/Sales-Trends/Market-Report/2011/9/bEU-2010b-E-bikes-Rising-Star-in-All-Major-Markets-BIK005299W/. Accessed Feb 5 2016

Bike Europe Web Site [Internet] (2016b) Speed e-bike sales scores 30 % growth in Holland. http://www.bike-eu.com/sales-trends/nieuws/2016/1/speed-e-bike-sales-scores-30-growth-in-holland-10125408. Accessed 10 Jan 2016

de Geus B, Van Hoof E, Aerts I, Meeusen R (2008) Cycling to work: influence on indexes of health in untrained men and women in Flanders. Coronary heart disease and quality of life. Scand J Med Sci Sports 18(4):498–510

de Geus B, Joncheere J, Meeusen R (2009) Cycling to work: influence on indexes of health in untrained men and women in Flanders: minimum dose to improve indexes of fitness. Scand J Med Sci Sports 19(2):179–187

de Geus B, Kempenaers F, Lataire P, Meeusen R (2013) Influence of electrically assisted cycling on physiological parameters in untrained subjects. Eur J Sport Sci 13(3):290–294

Donnelly JE, Honas JJ, Smith BK et al (2013) Aerobic exercise alone results in clinically significant weight loss for men and women: midwest exercise trial 2. Obesity 21(3):E219–E228

Dunstan DW, Kingwell BA, Larsen R et al (2012) Breaking up prolonged sitting reduces postprandial glucose and insulin responses. Diabetes Care 35(5):976–983

Durstine JL, Grandjean PW, Davis PG, Ferguson MA, Alderson NL, DuBose KD (2001) Blood lipid and lipoprotein adaptations to exercise: a quantitative analysis. Sports Med 31(15):1033–1062

Durstine JL, Grandjean PW, Cox CA, Thompson PD (2002) Lipids, lipoproteins, and exercise. J Cardiopulm Rehabil 22(6):385–398

Frank LD, Andresen MA, Schmid TL (2004) Obesity relationships with community design, physical activity, and time spent in cars. Am J Prev Med 27(2):87–96

Freedson PS, Melanson E, Sirard J (1998) Calibration of the Computer Science and Applications, Inc. accelerometer. Med Sci Sports Exerc 30(5):777–781

Gojanovic B, Welker J, Iglesias K, Daucourt C, Gremion G (2011) Electric bicycles as a new active transportation modality to promote health. Med Sci Sports Exerc 43(11):2204–2210

Grant RW, Dixit VD (2015) Adipose tissue as an immunological organ. Obesity 23(3):512–518

Healy GN, Dunstan DW, Salmon J et al (2007) Objectively measured light-intensity physical activity is independently associated with 2-h plasma glucose. Diabetes Care 30(6):1384–1389

Hendriksen IJ, Zuiderveld B, Kemper HC, Bezemer PD (2000) Effect of commuter cycling on physical performance of male and female employees. Med Sci Sports Exerc 32(2):504–510

Herman Hansen B, BØrtnes I, Hildebrand M, Holme I, Kolle E, Anderssen SA (2014) Validity of the Actigraph GT1M during walking and cycling. J Sports Sci 32(6):510–516

Hoehner CM, Barlow CE, Allen P, Schootman M (2012) Commuting distance, cardiorespiratory fitness, and metabolic risk. Am J Prev Med 42(6):571–578

Levitan EB, Song Y, Ford ES, Liu S (2004) Is nondiabetic hyperglycemia a risk factor for cardiovascular disease?: a meta-analysis of prospective studies. Arch Intern Med 164(19):2147–2155

Louis J, Brisswalter J, Morio C, Barla C, Temprado JJ (2012) The electrically assisted bicycle: an alternative way to promote physical activity. Am J Phys Med Rehabil 91(11):931–940

Mansoubi M, Pearson N, Biddle SJ, Clemes SA (2015) Using sit-to-stand workstations in offices: is there a compensation effect? Med Sci Sports Exerc. doi:10.1249/MSS.0000000000000802

Matthews DR, Hosker JP, Rudenski AS, Naylor BA, Treacher DF, Turner RC (1985) Homeostasis model assessment: insulin resistance and beta-cell function from fasting plasma glucose and insulin concentrations in man. Diabetologia 28(7):412–419

Mayo Clinic Web Site [Internet] (2016) Barriers to fitness: overcoming common challenges. http://www.mayoclinic.org/healthy-lifestyle/fitness/in-depth/fitness/art-20045099. Accessed 4 Feb 2016

McKenzie B (2013) Out-of-state and long commutes: 2011. US Censes Bureau

McKenzie B, Rapino M (2011) Commuting in the US: 2009. US Census Bureau

Roca J, Agusti A, Alonso A et al (1992) Effects of training on muscle $O_2$ transport at $\dot{V}O_2$max. J Appl Physiol 73(3):1067–1076

Saydah SH, Miret M, Sung J, Varas C, Gause D, Brancati FL (2001) Postchallenge hyperglycemia and mortality in a national sample of US adults. Diabetes Care 24(8):1397–1402

Sperlich B, Zinner C, Hebert-Losier K, Born DP, Holmberg HC (2012) Biomechanical, cardiorespiratory, metabolic and perceived responses to electrically assisted cycling. Eur J Appl Physiol 112(2):4015–4025

Statista Web Site [Internet] (2016) Projected worldwide sales of electric bicycles in 2018 by region (in million units). http://www.statista.com/statistics/255658/worldwide-sales-of-electric-bicycles-by-region/. Accessed 10 Jan 2016

van Kruijsdijk RC, van der Wall E, Visseren FL (2009) Obesity and cancer: the role of dysfunctional adipose tissue. Cancer Epidemiol Biomark Prev 18(10):2569–2578

World Health Organization (2010) Global recommendations on physical activity for health. World Health Organization, Geneva