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Comparing physical activity of pedal-assist electric bikes with walking and conventional bicycles

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ABSTRACT

This paper presents a study on physical activity implications of electric bikes, focusing on the users of an on-campus conventional bicycle and e-bike sharing system at the University of Tennessee. The study describes field trials of 17 users of the bikesharing system and investigates physical activity metrics on identical trips made by three different modes: walk, conventional bicycle, and pedal-assist electric bicycle. The users completed a hilly 4.43 kilometer route using each mode. Heart rate and human power output were monitored along with GPS for each bout. In addition, the study used a laboratory test to relate oxygen consumption rate (VO_2 in ml/kg/min) and energy expenditure (EE kcal/kg/min) to user heart rate during bouts. Energy expenditure and ventilation rates (per minute) for all modes were not statistically different. However, total EE and VO_2 for each bout (per mile) for e-bikes are 24% lower than that for conventional bicycles, and 64% lower than for walking. This reflects the shorter travel time. Differences between e-bikes and bicycles are most pronounced on the uphill segment. Still, e-bikes provide moderate physical activity (MET > 3) on flat segments and downhill segments, and vigorous physical activity (MET > 6) on uphill segments. For e-bike trials, riders reported higher levels of enjoyment and lower need for a shower than walk or conventional bicycle trials. This paper adds to the expanding literature by comparing e-bike, bicycle and walk EE and VO_2. E-bikes can contribute as an active transportation mode to meet required physical activity guidelines.

1. Introduction

Electric assisted bicycles (hereafter e-bikes) are bicycles that require human pedal input to engage an electric motor drive system, also known as pedelecs. They have emerged in recent years as a new mode of sustainable transportation as well as a mode that serves as an active transportation option for individuals and communities. Increasing active transportation promotes physical activity (PA) and thus improves health by reducing the risk of chronic diseases and obesity rates (Sallis et al., 2004). To achieve significant health benefits associated with being physically active, adults are encouraged to acquire an equivalent of 150 min per week of moderate to vigorous physical activities (MVPA). This aerobic PA can be obtained by an individual at-home, during work or leisure-time, and active transportation (US Department of Health, 2008). Additionally, active transportation can support other transportation or

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environmental goals such as congestion, parking costs, energy consumption, and greenhouse gas emissions (Litman, 2009). At the community-level, many cities across the world are now developing bikeshare programs, in part to improve access to physically active modes (Fishman et al., 2015; Rojas-Rueda et al., 2011). Recent bikeshare deployments are integrating e-bikes and questions remain about their relative PA impact. For clarity, some types of e-bikes do not require pedal assistance, but rather control power through a throttle. Those types of e-bikes are excluded from the literature discussed below and are not relevant to this study.

Many authors have explored the impacts of active transportation modes on physical health. Use of active transportation modes is associated with health benefits such as reduced likelihood of obesity, reduced risk of cardiovascular disease, and reduced likelihood of diabetes (Gordon-Larsen et al., 2009; Pucher et al., 2010). Those who use active transportation modes for at least some part of their commute are also shown to engage in other physical activities for exercise and recreation (Terzano and Morckel, 2011). Furthermore, involvement in active commuting has been shown to reduce the risk of all-cause mortality and to have other positive benefits such as increasing the number of years lived without cardiovascular disease (Ferrucci et al., 1999; Franco et al., 2005; Jonker et al., 2006). Even in populations of smokers, higher levels of PA result in more years of life expectancy as well as more years of life without disability (Ferrucci et al., 1999). Among a prospective cohort study of adults in living near Copenhagen, active transportation to work via cycling was associated with a 40% decreased risk of mortality, even after controlling for other sources of aerobic PA (Andersen et al., 2000).

At the population-level, the estimates of adults who acquire aerobic PA via transportation cycling are somewhat limited. Among those countries who monitor the proportion of adults who do cycle to work, a wide range is reported, with a low less than 2% (Australia, Canada, Ireland, Switzerland, UK, and the USA) to a high of greater than 20% (China, Denmark, and the Netherlands) (Hallal et al., 2012).

E-bike user PA has been assessed in several empirical studies. In a laboratory experiment, trained and untrained cyclists rode on stationary trainers according to a fixed riding cycle finding that even high-assist e-bikes can still provide moderate (> 3.0 MET) PA (MPA) (Louis et al., 2012). E-bikes have also been shown to increase the amount of PA by older adults, effectively prolonging their ability to cycle (Johnson and Rose, 2015). Another study, the most recent, evaluated 20 pedelec e-bike riders over four-week period, where they were instructed to commute three days per week by e-bike. That study found significant improvements in health markers (e.g. glucose, maximum oxygen cost, and maximum power) after the trial (Peterman et al., 2016). Moreover, several perception studies have found that health is a primary motivation of early adopters of e-bike owners in North America (MacArthur and Kobel, 2016), Europe (Jones et al., 2016), and Australia (Johnson and Rose, 2015).

Controlled trials are required to understand the impact of e-bike technology, that is not confounded by behavioral shifts or self-selection bias. Four European studies (Berntsen et al., 2017; Gojanovic et al., 2011; Simons et al., 2009; Sperlich et al., 2012) have explored the impacts associated with riding pedelec e-bikes as a mode of active transport. All studies conducted controlled small-sample experiments of e-bike PA relative to bicycling and walking. This study aims to contribute to this body of literature by overcoming some of the limitations of those efforts. In all studies, they found that e-bikes can provide at least moderate levels of PA, while reducing energy expenditure and exertion relative to conventional bicycling. The earliest study (Simons et al., 2009) is limited by its flat course, diminishing the ability to assess terrain differences. They do not assess walking as an alternative. And, the study lacks use of a conventional bicycle for comparison; the authors used a (heavy) e-bike without using the motor as surrogate for a conventional bicycle. The next study, (Gojanovic et al., 2011) explores conventional bicycling, e-bikes, and walking, but is limited to a very steep one-way uphill course (34 m of elevation gain per km), again limiting the ability to test terrain effects. As such, all trials (even walking) resulted in vigorous PA (VPA) levels. The most recent study, (Sperlich et al., 2012) is closest in design to ours, testing conventional bicycling and e-bikes over a hilly course. This study is limited because the sample only includes eight sedentary women and does not test a walking trial. The most recent study (Berntsen et al., 2017) investigates cycling and e-bike riding in Norway and found e-bike riders, while spending less time and effort cycling, still provide moderate PA.

This study aims to build on these previous findings by considering the impact of e-bikes on the physical activity of users, specifically focusing on energy expenditure (EE) and oxygen ventilation rate (VO_2). Our study includes 17 adults and includes walking, bicycling, and e-bike trials over a fixed hilly course. From this experiment, we are able to test across modes, gender, and terrain. This study considers quasi-experimental methods that utilized individuals having prior access to bicycles and e-bikes through a familiar e-bike sharing system (cycleUshare), whose characteristics are explained by Langford et al. (2013). The paper is organized as follows. The next section discusses the study design and methods. Section 3 analyzes the results of the laboratory and field studies. Section 4 provides a discussion, specifically comparing our results with the findings from the three studies described above. The last section concludes by discussing the limitations of this study and provides recommendations for integrating e-bikes into health-oriented transportation policy.

2. Methods

This study focuses on measuring the physiological impact of walking, bicycling, and e-bike riding on a carefully controlled, but representative fixed course. This loop course included a mix of on-road and separated path facilities totaling 4.4 km in length, on and around the University of Tennessee campus, in Knoxville, Tennessee. The course was fully paved with either concrete or asphalt pavement surfaces. For purposes of the data analysis, the course was divided into three sections and began at the highest elevation. Segment 1 proceeded downhill for 1.6 km (net elevation change -33.2 m), Segment 2 traversed a flat segment for 1.8 km (net elevation change -0.3 m) and Segment 3 proceeded uphill for 1.0 km (net elevation change +33.5 m). The course was traversed clockwise and is shown in Fig. 1. Each participant completed four activities, a laboratory physiological test, and three trials on the designated course – walking, bicycling and e-bike. The users had previously used an e-bike share system that allowed access to both conventional bicycles and e-bikes and were familiar with both technologies.

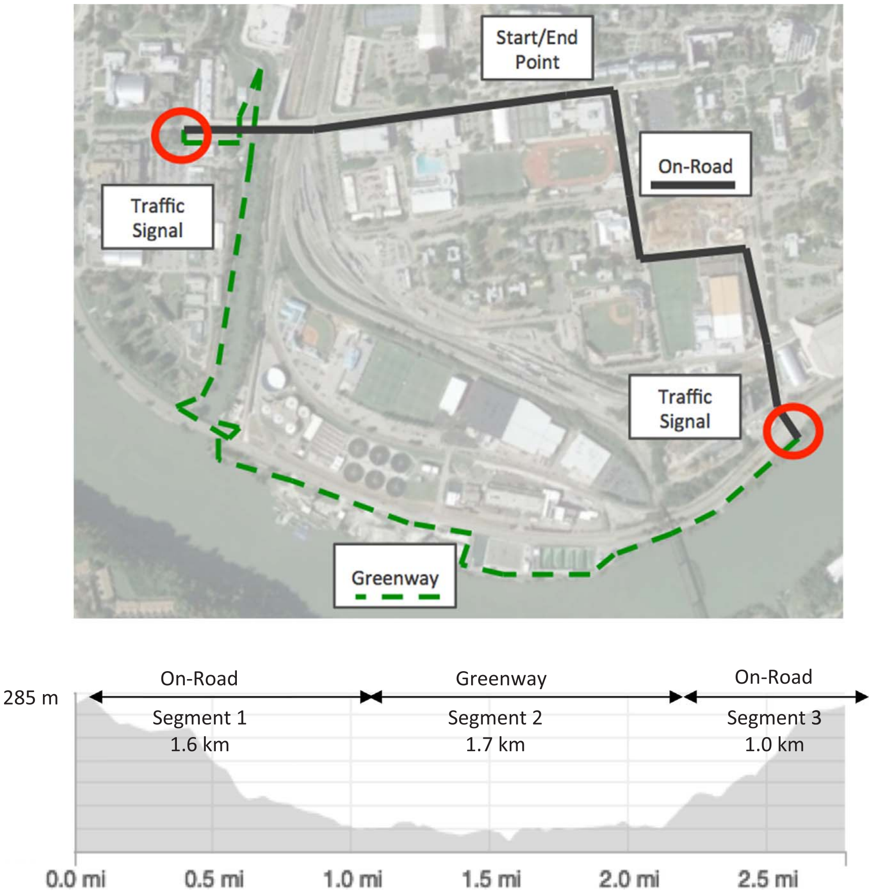

Fig. 1. Field trial course and elevation profile.

2.1. User participation

A sample (n = 17) of e-bike sharing system users (N > 100) volunteered to participate in this study. A summary of those volunteers is presented in Table 1. Inclusion criteria were that each participant be a registered user of cycleUshare, familiar with e-bike and bicycle technologies, and able to pass a physical activity readiness questionnaire (PAR-Q) (Canadian Society for Exercise Physiology, 2002) ensuring that the participant was healthy enough to complete the study. Prior to beginning the study, the participant's height and weight were measured. Other user information was verified through collection of updated consent forms for the e-bike sharing program. The participants represented a broad range of user characteristics as described by Table 1, and were representative of the e-bike sharing system users.

2.2. Lab testing

Each participant completed a laboratory test, where the user rode a stationary bicycle under varying levels of resistance. Subjects performed a graded exercise test on a cycle ergometer. Oxygen consumption and carbon dioxide production were measured via indirect calorimetry. Briefly, participants wore a nose-clip and breathed into mouthpiece attached to a Hans Rudolph one-way breathing valve, and expired gas was directed via a breathing tube to a ParvoMedics 2400 TrueOne Metabolic Measurement System. The oxygen and CO_2 analyzers within the system were calibrated prior to each test, using a tank containing known concentrations of mixed gas (16.0% O_2, 4.0% CO_2). The Hans Rudolph heated pneumotachometer, used to measure respiratory flow rate, was calibrated with a calibrated 3.0 L syringe. All VO_2 and VCO_2 values were corrected to Standard Temperature, Pressure, and Dry (STPD), and energy expenditure was computed using the Zuntz Table (Zuntz and Schumburg, 1901). Participant's heart rate, in beats per minute (bpm), oxygen ventilation rate (VO_2), in milliliters per kilogram per minute (ml/kg/min), and energy expenditure (EE), in kilocalories per minute (kcal/min) were measured at the end of each phase of resistance. Participants began the test with a two-min rest on the stationary bicycle. They then began riding at the lowest power output (100 watts) and increased by increments of 50 watts after each two-min phase until the participant reached 85% of age-predicted maximum heart rate (Center for Disease Control and Prevention, 2011), as described in Eq. (1).

$$85\%\ Age\ Predicted\ Heart\ Rate = (220 - Age) \times 0.85 \quad (1)$$

Table 1
Summary of Study Participants. (n = 17).

Sex	n
Male	11
Female	6
Age (years)	
< 20	3
20-25	6
26-30	4
31-40	2
41-50	0
> 50	2
Ethnicity	
White	12
Minority	5
Other:	
Own/have access to a bike	8
Own a car	15
BMI[a,b] (kg.m^{-2})	
Male	26.1
Female	23.1

[a] Values calculated using CDC formula for Body Mass Index (BMI) (Centers for Disease Control and Prevention, 2011).
[b] BMI values of users from this study (Mean = 25.0, Std. Dev = 4.1) were statistically the same as a sample of 1100 entering freshman at the University of Tennessee in 2006 (Mean = 23.4, Std. Dev = 4.5).

Values obtained in the lab test were used to correlate both VO_2 and EE to user heart rates, which was measured in the field trails. Curves were fit for each subject, and applied to their heart rate values measured during field trails. Based on the laboratory data, separate curves were fit above and below the heart rate inflection point, using the flex rate method, as observed for each user. This discontinuity in the linear relationship between HR and VO_2 or EE is well documented in the kinesiology literature (Leonard, 2003). Fig. 2 depicts fit lines for VO_2 and EE and their correlation coefficients for a typical participant. We also test the sensitivity of the flex rate discontinuity method to attain results, vis-à-vis a continuous linear regression. Participants were advised not to consume caffeine prior to laboratory testing as their heart rates could be affected.

2.3. Field trial technologies

This study used both a conventional bicycle and an e-bike, which are the same as those used by the e-bike sharing system. The conventional bicycle model used in the sharing system was a Marin Larkspur weighing approximately 30 pounds (13.6 kg). The e-bike used in this study was a Currie Technology I-Zip Trekking Enlightened model, which was modified for the sharing system and weighs approximately 60 pounds (27.2 kg), including the battery. This model of e-bike uses a 24V, 10Ah battery that connects to the rear of the e-bike to provide power to the e-bike motor (250W) when the user begins pedaling. It relies on Currie Technology's proprietary torque measurement method (TMM) to provide power to the motor proportional to the power supplied by the user through the pedals.

For this study both bicycle types were equipped with a Quarq SRAM S2275 MTB crank power meter, which replaced the existing

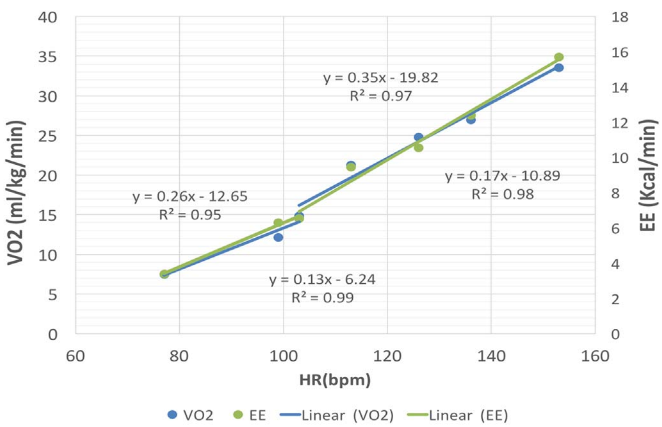

Fig. 2. Heart Rate Versus VO_2 and EE for a Typical Participant.

crank set, resulting in 16 gears (range 1:0.8 to 1:3.6) on the conventional bicycle and eight gears (range 1:1.2 to 1:3.3) on the e-bike. This model of power meter was selected since the gear ratio is similar to that used by the bicycles in the sharing system; however, with the power meter installed, conventional bicycles were limited to two front chainrings, slightly reducing the range of gear ratios within the original equipment. For the e-bikes used in this study, there was no change in the range of gear ratios. The power meters installed and calibrated at a bike shop according to installation guide and were zeroed prior to the beginning of each trial.

Study participants also wore Garmin heart rate monitors during all trial. Prior to beginning each trial, the heart rate monitors and Quarq power meters were synchronized with a Garmin Edge 500 GPS receiver to provide a data point for each second during the trial. All the data were then extracted in Microsoft Excel and filtered to eliminate any recorded points prior to the beginning as well as to eliminate points collected after the trial ended.

2.4. Field trials

Following completion of laboratory testing, participants completed a series of trials using three active transportation modes: walking, conventional bicycle riding, and e-bike riding. These three modes represent the dominant modal alternatives for users of the bikesharing system (Langford et al., 2013). These trials were conducted on separate days, with a minimum of 24 hours of rest between trials, to ensure the participant was not affected by a previous test. Each test followed a predefined 4.4 km route consisting of varying grade changes described in Fig. 1.

Each participant began the field trail portion of the study by walking the course, allowing the participant to learn the route while minimizing the risk of unnecessary stops or other navigation errors during the trial. Only one user travelled wrong way (4.5% of track length) before returning to the correct path. Following completion of the walking activity, conventional bicycle and e-bike trials were completed in random order on subsequent testing days.

During each trial, the participant's heart rate, power output, and speed were recorded at a one-second resolution. Figs. 3 and 4 illustrate of the power, speed, VO_2, and EE data for one participant during each trial type (Note: power only available for bicycle and e-bike trials). Participants were instructed to ride or walk at an intensity they would normally adopt when completing a utilitarian (i.e., non-exercise) trip on campus. Based on observations of the bikeshare users, e-bike riders often select the highest assist-level on the e-bike, out of five levels. Thus, for e-bike trips, participants were instructed to use the highest assist-level on the e-bike for the entire trial.

The field trials took place between March 19, 2013, and May 9, 2013. During this time period, weather conditions varied with ambient temperatures ranging from 0 °C to 28 °C at the time of testing. No trials were conducted when temperatures were below 0 °C and participants were provided the option to reschedule testing if they felt the weather conditions would affect them. We used a handheld anemometer (wind speed gauge) only to verify that the wind speeds were not excessive. Also, no trials were conducted on days with rain or a strong chance of rain.

2.5. Post activity survey

Following each trip, participants were presented with post-activity surveys. These surveys asked users about the trip they just

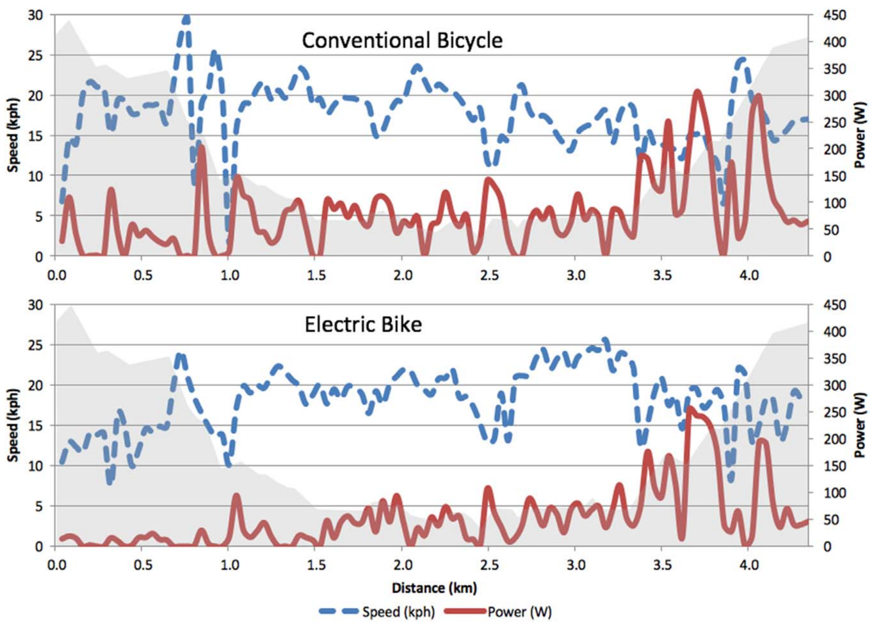

Fig. 3. Illustrative Power and Speed Measurements for a typical study participant by bicycling and e-bike riding. Elevation profile shown in grey.

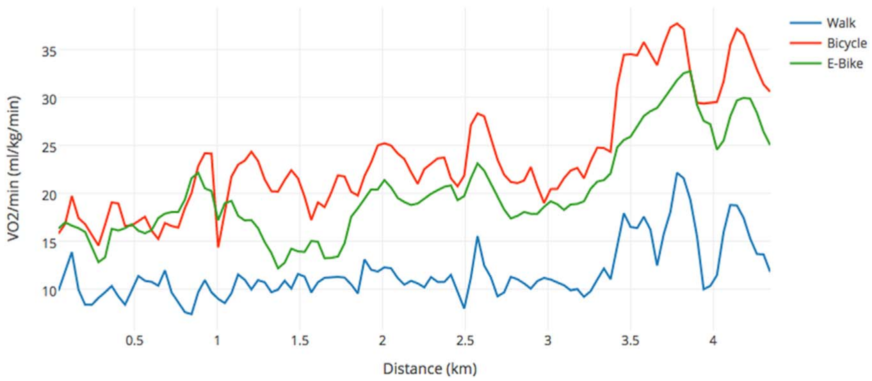

Fig. 4. Illustrative VO_2 Measurements for a typical study participant, by walking, bicycling, and e-bike riding.

completed with regard to a number of qualitative metrics including level of enjoyment, level of exertion, and need for a shower. Perceived exertion was measured using the Borg Rating of Perceived Exertion (RPE) scale. These surveys were also used to identify any problems that may have arose during the trip that might have potentially affected the overall outcome, for example long delays at traffic signals.

3. Analysis and results

Of the 17 participants who began the study, all of them completed a walking trip, but only 16 completed both an e-bike trip and a conventional bicycle trip. Performance on the course was studied for each participant, and heart rate measurements collected during each trip was used to estimate EE and VO_2, based upon the relationships between EE and heart rate observed in the laboratory. These estimated rates of energy expenditure for each minute of the trip were then summed to provide a measure of total calories expended and VO_2 consumed during the trip. In both EE and VO_2, we normalized by weight to offer consistent comparisons. The normalized VO_2 values were used to determine average Metabolic Equivalent of Task (MET) for each trip, where one MET is equivalent to 3.5 ml per kg per min. For the two traffic signals on the route, we removed all the associated data if the participant was delayed by the signal, only including moving data. For all participants we looked at their GPS tracks and removed data representing stopping or coasting during the wait.

Table 2 summarizes the metrics for each trip mode by segment. Except walking, due to the lack of power data, we conducted repeated measures ANOVA to examine the significance of the difference between modes and across segments. A paired t-test was also used to examine differences for power between bike and the e-bike. Across all metrics there were significant interactions between mode and type of segment (downhill, level, and uphill). Travel time was statistically different between each mode for all the segments, $F(4, 48) = 156.0$, $p < 0.001$. Longer trip times produced greater Total EE (Kcal/kg) and VO_2 (L/kg) for walking trials compared to conventional bicycle and e-bike trials. E-bike trials have the lowest Total EE (Kcal/kg) and VO_2 (L/kg) rates, reflecting

Table 2
Summary statistics from field trials by mode and segment.

Segments		**Walk (n = 16)**			**Bike (n = 13)**			**E-Bike (n = 16)**		
		1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Trial Time (min)	**mean**	17.7*	19.8*	11.4*	6.0*	6.2*	5.7*	5.5	5.7	4.5
	SD	(1.49)	(1.47)	(1.45)	(0.91)	(0.55)	(0.96)	(0.78)	(0.75)	(0.82)
Power (watts)	**mean**	–	–	–	52.4*	93.0*	117.4	36.3	62.4	98.3
	SD	–	–	–	(16.5)	(22.4)	(27.7)	(18.9)	(28.2)	(25.8)
Heart Rate (bpm)	**mean**	109.5	114.0	126.5*	111.3	121.3	152.1*	109.5	118.2	140.3
	SD	(13.1)	(14.7)	(16.6)	(12.9)	(30.1)	(17.0)	(13.1)	(19.5)	(20.5)
Segment Total EE (Kcal/kg)	**mean**	1.14*	1.41*	1.05*	0.41*	0.57*	0.75*	0.34	0.44	0.52
	SD	(0.46)	(0.55)	(0.33)	(0.18)	(0.24)	(0.13)	(0.13)	(0.14)	(0.14)
Average EE	**mean**	0.71*	0.80*	1.09*	0.25*	0.32*	0.78*	0.21	0.24	0.53
(Kcal/kg/km)	**SD**	(0.29)	(0.31)	(0.35)	(0.11)	(0.13)	(0.13)	(0.08)	(0.08)	(0.14)
Average EE rate (Kcal/kg/min)	**mean**	0.07	0.07	0.09*	0.07	0.09	0.13*	0.06	0.08	0.12
	SD	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)	(0.02)	(0.02)	(0.03)	(0.03)
Segment Total VO_2 (L/kg)	**mean**	0.23*	0.29*	0.21*	0.08*	0.11*	0.15*	0.07	0.09	0.10
	SD	(0.09)	(0.11)	(0.07)	(0.04)	(0.05)	(0.03)	(0.03)	(0.03)	(0.03)
Average VO_2 rate (ml/kg/min)	**mean**	13.4	14.6	18.6*	13.8	18.2	26.6*	13.0	15.9	23.2
	SD	(5.25)	(5.56)	(5.42)	(5.18)	(7.57)	(4.72)	(4.81)	(6.05)	(5.10)

Segment: 1 = downhill; 2 = level; 3 = uphill.
* Comparison with E-bikes significant at > 95% confidence interval.

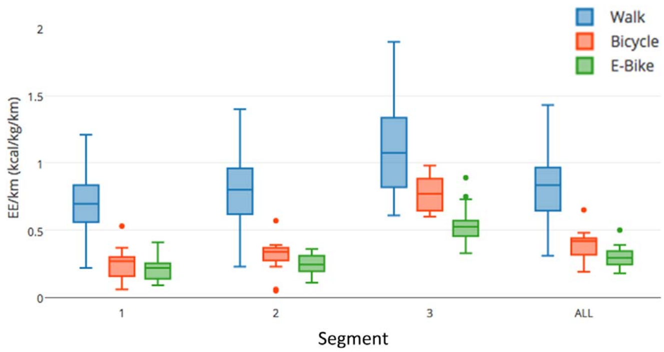

Fig. 5. Segment-wise difference in rate of Energy Expenditure (EE).

the higher average travel speeds for that mode compared to the other modes. Also, lower average EE (Kcal/min) and VO_2 (ml/kg/min) rates compared to conventional bicycle trials shows lower requirements on e-bike trips for user-supplied power than conventional bicycle trips. For the uphill portion (Segment 3), the average EE (Kcal/kg/min) and VO_2 (ml/kg/min) values for e-bikes trials fall between walking and bicycle trials (33% higher than walking and about 8% lower than conventional bicycle). The power applied by the user was lower (though not statistically significant for Segment 3) for e-bikes than for regular bicycles. The average Heart Rates, while lower for e-bike users than regular bicycle, only reached significance in segment 3, the uphill segment, $F(1.8, 21.7) = 6.1$, $p = 0.009$.

Fig. 5 shows the total EE rate interaction for all three modes for each of the three segments, $F(2.6, 31.4) = 20.9$, $p < 0.001$. On average, e-bikes require 24% and 64% less total EE than conventional bicycles and walking for the trial, respectively. The differences between conventional bicycles and e-bikes were less pronounced for downhill (Segment 1) and flat (Segment 2) segments, with 16% and 23% lower total EE, contrasted with the uphill Segment 3 where e-bike EE was 31% lower than the conventional bicycle. This pattern contrasts the comparison with the walk trial, where e-bike total EE was 70%, 69%, and 50% lower for Segment 1 (downhill), Segment 2 (flat), and Segment 3 (uphill), respectively. The walking EE rate (kcal/kg/km) is about 30% higher for Segment 3 than Segments 1, closing the gap between walking and e-bike riding (Fig. 5).

We use HR to estimate VO_2 and EE based on a discontinuous regression method (flex rate method to account for heart rate inflection). We reanalyzed the data using a continuous regression approach (i.e., fitting a single line through the HR and VO_2 and EE data) and found the results were stable relative to those reported here. The continuous regression method results the same direction and magnitude differences between trials, modes, and segments. The results (values) for the continuous regression method were all lower than the flex rate method, by less than 2%. The key comparative results are as follows: compared to e-bike, bicycle average total EE (kcal/kg) is 28.8% higher (flex rate method) and 32.8% higher (continuous method); and walking average total EE (kcal/kg) is 177.4% higher (flex rate method) and 176.9% higher (continuous method). Segment level results (by mode) mimic the subset presented here.

3.1. Within-subject analysis

We analyzed data within subject to discover any nuanced findings that could have influenced our results. For example, we observed some subjects riding an e-bike at high intensity, but in shorter travel time, moderating their overall EE. Most subjects rode e-bikes and bicycles at medium intensity, also resulting in moderate EE. Last, some subjects rode both bikes with low intensity but for longer periods, resulting again in moderate overall EE. Aggregating and averaging the data loses some resolution in this finding. Fig. 6 shows the within-subject analysis for e-bike and bicycle by segment, with energy intensity (expressed as MET) on the top panel and energy expenditure (per distance) on the bottom panel. To illustrate, on average, e-bike riders experienced MPA ($3 < MET < 6$) on Segment 1 (downhill) and Segment 2 (flat), one subject (3) experience vigorous PA (VPA) ($MET > 6$) on Segment 1 and four subjects (2, 3, 9, 14) on Segment 2. Meanwhile, five (6, 7, 10, 12, 15) and three (6, 12, 15) e-bike subjects experience Light PA (LPA) ($MET < 3$) on Segment 1 and Segment 2, respectively; and the three subjects who experienced LPA in Segment 2 also experience LPA in Segment 1. On average, e-bike riders experienced VPA on Segment 3 (uphill), but four subjects experienced MPA, with no LPA subjects; even the LPA subjects from Segments 1 and 2 moved to MPA on Segment 3. In all cases, MET levels were monotonically increasing between segments, for the same subject, i.e., users increased intensity from downhill to flat to uphill segments as expected. In most (but not all) cases, the e-bike energy intensity (MET) was lower than the bicycle for all subjects. On Segment 3 (uphill), three subjects rode at higher intensity on e-bike than bicycle (subjects 9, 10, 14). However, total energy expenditure (EE/kg/km) for two of those riders was lower, i.e., they exerted energy at a higher rate, for a proportionally shorter period of time. With very few exceptions, riders exerted lower total energy on all segments by e-bike than bicycle. On Segment 3, the difference between e-bikes and conventional bicycles is visually distinct for total energy expenditure per kilometer, but the difference is less distinct for energy intensity, showing that subjects still exert high (mostly VPA) energy intensity on e-bike, but the overall EE is diminished by lower travel (bout) time, resulting in larger gaps between bicycle and e-bike.

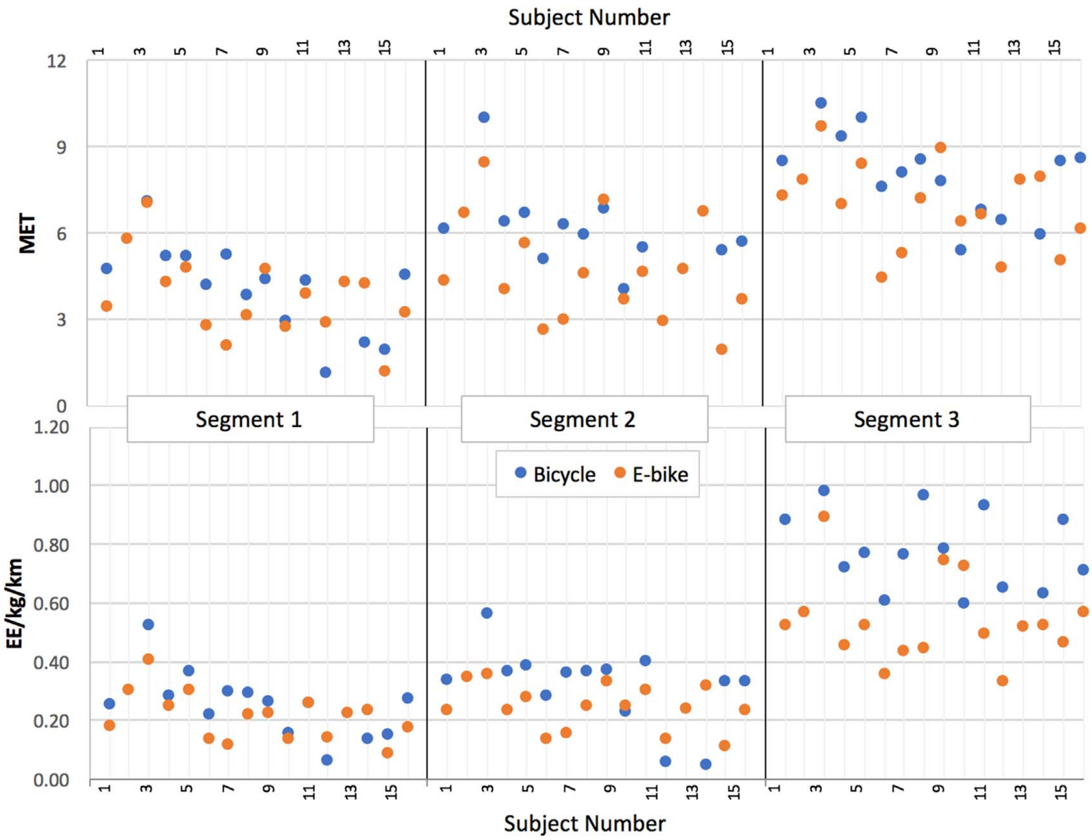

Fig. 6. Within-subject Total EE and PA Levels for Bicycle and E-bike by Segment.

3.2. Gender and bicycle ownership effects

We compared EE and VO_2 (total and rate) within mode between genders. As expected, males require more EE and VO_2 than females, but this difference vanishes when normalizing for weight. We conclude that, across modes, females do not differ from males in terms of normalized energy expenditure or ventilation rate. Similarly, we compared between populations that owned personal bicycles compared to those without a personal bicycle and found no significant differences between any of the parameters we measured.

3.3. Post-activity survey responses

Comments received in post-activity surveys for each completed trial revealed that some users (n = 3), on both conventional bicycles and e-bikes, experienced difficulty on Segment 3 involving uphill grades, though only two took longer time than average. However, when asked about level of enjoyment using a five-point Likert scale, participants responded favorably after trials from both bicycle types. Fig. 7 shows the level of enjoyment reported following each trial. Participants completing e-bike trials responded most favorably with 56% indicating that the trial was *Very Enjoyable*, compared to only 31% of the conventional bicycle trials and 24% of walking trials. Only 6% of respondents rated the e-bike trip *Unenjoyable* or *Very Unenjoyable*, in contrast with 19% and 24% for conventional bicycling or walking trials, respectively.

Participants were also asked about their perceived level of exertion for the entire trip, using the Borg scale of exertion (Borg, 1982). Exertion perceptions did not vary by gender. The perceived exertion levels for participants after e-bike trials (mean 9.3 ± 2.6 S.D.) was not significantly different than responses after walking trials (9.2 ± 2.2), but both were lower than conventional bicycle exertion (13.4 ± 2.3). We also asked about their perceived need to shower, an important barrier to transportation cycling (De Geus et al., 2009). Fewer participants responded that a shower was needed after completing the e-bike trail (25%) than after the other trials (walk:35%, bicycle: 56%), demonstrating the perception among users that e-bike trips are less physically demanding compared to the other trip types.

4. Discussion

This work expands the body of literature on the physiological demands of using an e-bike to increase PA. Although walking

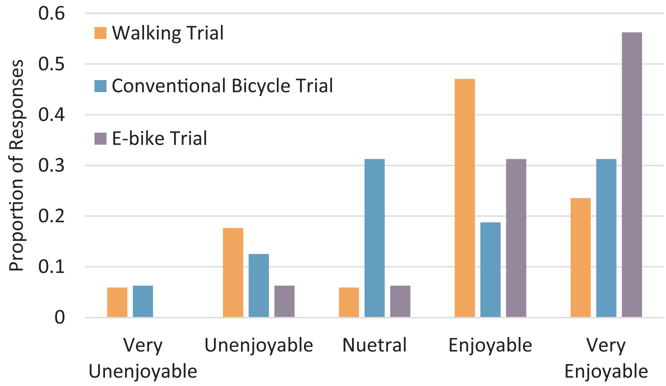

Fig. 7. Stated level of enjoyment during trial.

requires the least amount of EE per unit time of the modes considered, on the course used in this study the total EE (i.e., EE per unit distance) for e-bike trips was 24% less than that of conventional bicycle trips and 64% less than that of walking trips due to the lower duration of time required to complete the trip for each mode. Differences in EE correlate perfectly with total VO_2 ventilation. An important distinction between leisure time PA and transportation related PA is that transportation related PA (i.e., trips) are usually expressed in terms of distance, whereas leisure time PA (i.e., bouts) are usually expressed in terms of time. In this sense, for trips of equal length (e.g., 4.4 km), the e-bike requires less total EE (Kcal/km) than the bicycle and walking. By contrast, for a set duration bout (e.g., 30 min), e-bikes require less EE (Kcal/min) than bicycle (13%) and more EE than walking (14%), though the energy expenditure rate between the e-bike and other modes was not significantly different.

Per minute, an e-bike can still provide moderate levels of PA. With a mix of downhill, flat, and uphill sections we found that, all modes provide moderate levels (MET > 3) of physical activity (MET 4.5, 5.8, and 5.1 for walk, conventional bicycle, and e-bike, respectively). Looking at individual segments, Segment 1 (downhill) resulted in similar MET values of 3.8, 3.9, and 3.7; Segment 2 (flat) resulted in MET values of 4.1, 5.2, and 4.5; and Segment 3 (uphill) resulted in MET values of 5.3, 7.6, 6.6 for walk, conventional bicycle, and e-bike, respectively. The conventional bicycle and e-bike both provided vigorous physical activity (MET > 6) on the uphill segment. The uphill segment is where there is a notable difference between e-bikes and bicycles, where e-bike riders EE goes up, but does not see the same large jump as bicycle riders' EE (see Fig. 6). The e-bike total EE/kg/km remains relatively stable across segments, indicating that in the uphill segment, the e-assist is contributing more motive energy. Indeed, this is one of the key advantages toward the uptake of e-bikes, effectively removing terrain barriers as demonstrated here. In contrast, the difference between bicycle EE/kg/km for Segment 2 and 3 is dramatic (Fig. 6), which could be a deterrent to cycling.

4.1. Comparison with previous work

Our study builds on previous research comparing the physiological impacts of different modes of active transportation. This study most closely mirrors the methods and approach of Sperlich et al. (2012), with both having a hilly natural course trial. However, that study was limited to sedentary women, and did not include walking comparisons. The difference in total EE for e-bikes compared to conventional bicycles was slightly lower for our study (24% compared to 33%) than in Sperlich et al. (2012). The difference in power output was the more in our study, 26% compared to 13% lower average power (W) for e-bikes. In our study HR did not statistically vary between e-bike and conventional bicycle for the whole trip, consistent with similar rates of EE between the two modes. However, the difference in the rates of EE and HR was significant for the third uphill segment. Sperlich et al. (2012) also showed higher HR for cyclists. The total EE is different between modes based on different durations of the trials. In short, the work here presents very similar findings. This work, however, goes one step further and studies a more varied set of participants and assesses e-bikes compared to walk-trips, the predominate replaced mode of bikeshare in our previous study (Langford et al., 2013).

Another earlier study included both walking and conventional bicycling with e-bike trials at two power levels (standard and high) (Gojanovic et al., 2011). The findings in Gojanovic et al. (2011) follow the same trends here and in Sperlich et al. (2012), though the predominately uphill course tends to result in higher HR, VO_2, and EE, and lower speeds.

4.2. Exertion, enjoyment, and need to shower

Sperlich et al. (2012) and Gojanovic et al. (2011) both use a Borg scale of exertion. In both cases, the results are similar to the findings in this study. In this current study, for conventional bicycling, the mean level of exertion (13.4) was about one point lower than Sperlich et al. (2012) and two points lower than Gojanovic et al. (2011) (likely owing to terrain difference). For the e-bike in this study, level of exertion (9.3) was about one point higher than Sperlich et al. (2012) and one point lower than Gojanovic et al. (2011).

For level of enjoyment, we had similar findings as Sperlich et al. (2012), with enjoyment about one point (category) higher for an e-bike than a conventional bicycle. In our study, e-bike exertion was about the same as walking, and level of enjoyment was about 0.6 points higher than walking.

Gojanovic et al. (2011) also asked about the need for a shower after each trial, and more of their subjects required a shower after the bicycle trial, again, perhaps owing to the predominately uphill course. More of our walk participants reported needing a shower, likely because of our long walk course relative to Gojanovic et al. (2011). Even though perceived exertion of walking and e-bike trials were the same in our study, lower need to shower for e-bike trial could be because of the substantially shorter duration of the e-bike trial.

5. Conclusion

This paper focuses on investigating comparisons between trips made on e-bikes, conventional bicycles, and walking. As expected, e-bike power demands from the user are lower than those of conventional bicycles; however, e-bikes can be a technology to introduce active transportation to potential users, particularly sedentary individuals, and can be balanced by longer trip distances. Past literature suggests that e-bikes can serve as a gateway to active transportation for sedentary individuals (Sperlich et al., 2012). Users replacing a walking or conventional bicycle trip with an e-bike trip would be expected to acquire fewer MVPA physical activity minutes since that mode requires less energy than the alternative modes. Users replacing a car, bus, or other less active transportation trip with an e-bike trip would be expected to obtain more minutes of MVPA by choosing a more active transportation mode. We confirm this finding and support the recommendation that e-bikes, while providing less physical activity for transportation trips (of fixed distance) than the other active transport modes, still provide moderate levels of physical activity. Moreover, in hilly environments, an e-bike could be expected to allow the rider to obtain vigorous-intensity physical activity on uphill segments.

In this study, users were required to choose the highest power setting; however, users for more exercise-oriented trips can elect to reduce the motor power which would increase the physical activity intensity. We do not know what power setting users would have chosen in a naturalistic experiment. In addition, e-bikes promote longer trips and trips to multiple destinations (Langford et al., 2013), and have higher trip rates (MacArthur and Kobel, 2016). The added duration of e-bike trips could enhance the health benefits of e-bike riding by allowing the user to acquire minutes of MVPA which contribute to their meeting or exceeding the national guidelines for physical activity. In Langford et al. (Langford et al., 2013), e-bike trips were 13% longer than conventional bicycle trips. Still, this study did not explicitly test for both physical activity and behavioral effects of technology uptake.

This work also does not explicitly consider that under natural behavioral conditions, users of e-bikes could have different trip making behavior or employ different riding characteristics (e.g. route choice). Two studies recently considered this effect (De Geus et al., 2013; Peterman et al., 2016). Future research is needed to investigate how the naturalistic real-life e-bike and conventional bicycle use may vary and how it may affect the user from a physical activity standpoint. The extension of this study to naturalistic data, collected from instrumented conventional bicycles and e-bikes would be a strong next step in the research.

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