Original Research

Measuring Activity Energy Expenditure: Accuracy of the GT3X+ and Actiheart Monitors

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ABSTRACT

International Journal of Exercise Science 6(3) : 217-229, 2013. The purpose was to determine the accuracy of the GT3X+ and Actiheart monitors for estimating energy expenditure (EE) and steps. Additionally, to investigate agreement between waist- and wrist-mounted GT3X+ EE outputs. Nineteen participants (mean age=30) completed three treadmill walking trials at self-selected slow, medium, and fast speeds while wearing two GT3X+ (waist and wrist) and an Actiheart. Activity monitor EE was compared to indirect calorimetry criterion EE using Pearson correlations and ANOVAs. A Bland-Altman plot was used to investigate agreement between GT3X+ waist- and wrist-determined EE. GT3X+ determined steps were compared to researcher-counted steps using ANOVAs. EE estimates from all monitors correlated highly with the criterion (*r* ranged from .72 to .82). However, the GT3X+ (waist and wrist) underestimated EE during slow walking and overestimated EE during fast walking. There were no differences among GT3X+ (waist and wrist) estimates of EE and the criterion during the medium trial. Actiheart estimated EE was not significantly different from measured EE during all trials. The Bland-Altman plot indicated that at EE rates above 4 kcal·min^{-1}, the GT3X+ worn on the wrist underestimated EE compared to when it was worn on the waist. There were no differences between GT3X+ waist-determined steps and researcher-counted steps for all trials. GT3X+ EE correlates highly with measured EE, but has poor absolute agreement during slow and fast walking. GT3X+ step estimates are accurate across the continuum of walking speeds when waist (but not wrist) mounted. Wrist-mounted device outputs are not comparable to waist-mounted outputs. The Actiheart accurately estimates EE.

KEY WORDS: Accelerometer, Actigraph, Actiheart, walking, validity

INTRODUCTION

The current obesity pandemic burdens health systems across the world. This burden is likely to increase as more countries adopt increasingly sedentary lifestyles and increasingly unhealthy diets (11). Obesity is the result of complex interactions among energy intake, energy expenditure (EE), genetic characteristics, and environmental determinants (2). A better understanding of the relationships among these factors may contribute to the control of this preventable disease. In order to improve our understanding, accurate measures of each component are needed. Of the two behavioral contributors to obesity (energy intake and EE), energy intake can be estimated using techniques such as weighed food intake and detailed food diaries (13). Although somewhat impractical, and not error-free, these techniques provide relatively accurate and reliable estimates for the energy intake side of the energy balance equation.

Energy expenditure is arguably more difficult to estimate using practical and affordable measures, and typically requires cumbersome or expensive techniques such as indirect calorimetry or doubly-labeled water to obtain accurate measurements (25). Affordable ambulatory monitors that provide precise estimates of physical activity-related EE may provide important information to help understand the energy balance relationship. However, there is a lack of evidence for the accuracy of such measures for estimating EE in a metric that is comparable to energy intake (i.e., so that imbalances between energy intake and expenditure may be quantified).

The Actigraph GT3X+ (Actigraph Inc., Pensacola, FL) is a new tri-axial accelerometer that provides data on several physical activity-related outcomes. This activity monitor is relatively new and therefore few studies have investigated its validity. Rowlands and Stiles (2012) found that GT3X+ acceleration values correlated between r = 0.59 and r = 0.87 with various measures of ground reaction force, and so the device shows promise for use in studies related to bone health. They also found that raw acceleration outputs differed between waist- and wrist-worn devices during brisk walking, whereby waist-worn devices provided higher outputs than wrist-worn devices (19). In another study, Carr and Mahar (2012) investigated the accuracy of the GT3X+ for measuring time spent in sedentary and light intensity activity, and also investigated the accuracy of the device's inclinometer function. They found that the GT3X+ correctly estimated more than 80% of time in sedentary activities and between 23.7% and 75.5% of time spent in light activities. The inclinometer function of the GT3X+ correctly identified anatomical position between 60.6% and 66.7% of the time during sedentary activities (7). Finally, two other studies have been conducted to investigate agreement between different generations of Actigraph. One of these studies was conducted among adults (16) and the other among children and adolescents (17). These two studies investigated the inter-instrument agreement among several generations of Actigraph (including the GT3X+). However, they did not report on the accuracy of the GT3X+ compared to a criterion measure. To the authors' knowledge, no study has been conducted to compare GT3X+ EE estimates to a criterion measure in adults.

The primary aim of this study therefore, was to investigate the accuracy of the GT3X+ monitor for estimating physical activity-related EE under controlled walking conditions by comparing EE outputs from this device to a criterion measure (indirect calorimetry) and another validated physical activity and EE monitor (Actiheart, CamNtech Ltd., Cambridge, UK). The secondary aim was to determine the accuracy of the GT3X+ for estimating steps during walking. The final aim was to investigate agreement between the GT3X+ for estimating EE when worn on two different body positions (i.e., waist and wrist). The National Health and Nutrition Examination Survey (NHANES) has recently changed its physical activity monitoring protocol. Participants now wear the accelerometer (GT3X+) on their wrist, rather than their waist, as they did in previous waves of data collection (8). The present study aims to determine whether this change in protocol will provide accurate estimates of physical activity EE.

It should be noted that the monitors in this study do not *measure* EE or steps *per se*, rather they measure raw acceleration which is then interpreted by inbuilt mathematical algorithms in order to estimate the outcome of interest. In this regard, it is more accurate to state that we are evaluating the data processing models rather than the devices themselves. Although the processes involved between measurement and estimation may be straightforward in some instances (e.g., steps), it is more complex when other variables are estimated (e.g., total energy expenditure). The final result obtained from these devices is therefore heavily dependent on the mathematical algorithms applied, and not entirely on the raw data generated by the device.

We selected walking as the physical activity of interest in this study because it is one of the most basic and widespread activities, and is an accessible entry-level activity for individuals with obesity. Furthermore, walking is rhythmic and repetitive, providing what should be distinctive movement patterns for the activity monitors to detect. If the devices demonstrate accuracy for estimating EE during walking, this would warrant further investigation of the devices during more complex free-living activities, such as gardening, household chores, or transport-related activities.

METHODS

Participants

Participants were 19 adults (13 males, 6 females) with a mean age of 30 years (range = 19-53 years). Prior to testing, each participant provided written informed consent, and completed a physical activity readiness questionnaire (PAR-Q) (23) to identify any contraindications to participation. Approval to conduct the study was granted by the Ethical Review Board at the College of Life Science and Medicine at the University of Aberdeen, Scotland. All procedures conformed to the standards of the Helsinki Declaration.

Measures

Actigraph GT3X+ accelerometer: The ActiGraph GT3X+ (ActiGraph Inc., Pensacola, FL.) is a small (4.6 cm x 3.3 cm x 1.5 cm) lightweight (19 g) tri-axial activity monitor that provides data on physical activity including activity counts, EE (kcal), steps, and activity intensity (METs). The device is waist- or wrist-worn on an elastic belt and activity is measured across three perpendicular planes. The GT3X+ has an inclinometer to determine body position (e.g., sitting, lying, and standing) and to identify periods of non-wear. Data (time varying accelerations in g's) are recorded in a raw format at a user-specified sampling rate between 30 Hz and 100 Hz, in 10 Hz increments, and the device has an integrated ambient light sensor that provides information on the wearer's environment. Data filtering and epoch selection are performed after data are collected, allowing datasets to be processed multiple times at different epoch selections and using different cut-points after the data have been collected. The device is water resistant up to 1 m for 30 min and data can be collected for up to 40 days, using the available memory of 512 MB. The GT3X+ costs $250, and is therefore considerably less expensive than other measures of EE such as calorimetry and doubly labeled water. Prior to data collection, devices must be initialized. This involves selecting a start time, participant ID, sampling rate, device position on the body, and entering demographic and anthropometric data including date of birth, gender, race, height, and weight. Data are downloaded via a USB cable and subsequent data processing is conducted using the proprietary Actilife software (e.g., epoch selection, wear-time validation, and EE estimation).

Actiheart accelerometer and heart rate monitor: The Actiheart (CamNtech Ltd., Cambridge, UK) is a combined accelerometer and heart-rate monitor that attaches to the chest via electrocardiography (ECG) pads. The device is comprised of three components: 1) a central circular unit (33 mm diameter) containing a piezo-electric accelerometer element, a battery, a non-volatile memory chip, and a clip that attaches to an ECG pad; 2) another small clip that attaches to a second ECG pad; and 3) a short (≈100 mm) wire connecting these two components. The accelerometer measures movement in the vertical plane and ECG signals are picked up via two ECG pads. One ECG pad is positioned at either V1 or V2. The other is positioned at either V4 or V5. The two ECG pads must be placed along the same horizontal plane for the accelerometer to function accurately. It has been shown that there are no differences in device output based on Actiheart position (i.e., upper chest vs. lower chest) (4). The device is initialized and data are downloaded by attaching the Actiheart to a docking station, which is in turn connected to a computer using a USB connection.

Prior to collecting data a signal test must be carried out. This requires the wearer to attach the ECG pads and wear the Actiheart for approximately 10 min to ensure that a strong heart beat signal with little noise is being detected by the monitor. Following a successful signal test, the device can then be initialized to begin collecting data. If the signal test is unsuccessful then a stronger signal may be achieved by moving the location of the ECG pads and repeating the signal test.

Several studies have investigated the validity and reliability of the Actiheart for measuring physical activity EE. Findings from these studies suggest that the Actiheart is an accurate measure of physical activity EE under controlled laboratory conditions among healthy adults (5), pregnant women (15), and children with chronic disease (22). It should be noted that several other studies have investigated the accuracy of another device called the Actiheart (3, 10, 21). The device referred to in these studies, however, is manufactured by a different company (Mini-Mitter Company Inc., USA) and uses different algorithms to estimate activity EE than the Actiheart in the present study.

Although there is strong validity evidence available for this device, the Actiheart is considerably more expensive than the GT3X+ (approximately $1500), and may therefore be less accessible to researchers with budgetary constraints. Additionally, the Actiheart is somewhat intrusive for the wearer and more labor-intensive for the researcher than the GT3X+. For example, participants need to remove clothing to attach ECG pads, and a successful signal test must be performed before data can be collected. One of the aims of this study therefore, was to determine if the GT3X+ may be used as a less expensive alternative to the Actiheart.

Indirect calorimetry: The criterion measure of EE was achieved using indirect calorimetry. Breath by breath $\dot{V}O_2$ and $\dot{V}CO_2$ were measured using the Ultima CPX (Medical Graphics, St. Paul, MN) in combination with BreezeSuite software (version 6.4.1; Medical Graphics, St.Paul, MN). The Ultima CPX is a non-portable apparatus that requires participants to insert a mouthpiece connected to an umbilical cord which in turn connects to a unit containing O_2 and CO_2 sensors. Participants wear a nose clip to ensure that all expired air is monitored.

Prior to data collection, the Ultima CPX was calibrated. This involved volume calibration via a large syringe which administered a known (3 liter) volume of air, and gas calibration using known concentrations of O_2 (21%) and CO_2 (5%).

Protocol

Participants provided information on their age and gender. Height was measured using a stadiometer (Holtain Ltd., Crosswell, UK) and weight was measured using weighing scales (Seca, Hamburg, Germany). Participants' resting heart rate was measured (beats per minute), and their predicted maximum heart rate (220 – age) and predicted sleeping heart rate (resting heart rate – 10) were also recorded. These values were subsequently used during the Actiheart initialization process. Barometric pressure was recorded prior to each testing session and entered into the gas analyzer for indirect calorimetry calculations. All testing was conducted in an environmental chamber with a consistent temperature of 18.0 °C and 50% humidity. Prior to testing, two GT3X+ devices were initialized and fitted to the participant (one on the right wrist and one on the right side of the waist), an Actiheart signal test was conducted, and the Ultima CPX was calibrated. The testing protocol was explained to participants and they were given the opportunity to familiarize themselves with walking on the treadmill and breathing while wearing the Ultima CPX mouthpiece and nose clip.

The testing protocol consisted of three treadmill walking trials, each lasting 10 min. Each of the trials was conducted at a different speed. For the first trial, participants were asked to walk at a speed that they thought was slow. Participants were asked to walk at a medium speed for the second trial. Finally, for the third trial participants were asked to walk at a speed that they thought was fast. The treadmill speed was controlled by the participant and not the researcher. Expired air was measured for the final 5 min of each trial (i.e., once participants had reached steady state), and steps were counted during the eighth min of each trial by a member of the research team. A digital watch was used to record the start and end times of each trial. The watch had been synchronized with the computer used to initialize the GT3X+s and Actiheart, allowing for exact time-stamps to be created. This was crucial for subsequent data processing. GT3X+s were selected from a pool of 15 devices and were set to record data at a sampling rate of 30 Hz. Actihearts were selected from a pool of 8 devices and sampled at 15 sec epochs, as this was the default sampling rate for the short-term advanced EE setting that was selected for data collection.

Data Processing

GT3X+: GT3X+ data were downloaded via a USB cable and uploaded into Actigraph's proprietary data processing software (Actilife version 6). For data generated from devices worn on the wrist, the 'Worn on wrist' option was selected during the data scoring stage. EE (kcal) was calculated for the final 5 min of each walking trial using the prediction equation developed by Sasaki, John, and Freedson (2011)(20), labeled the 'Freedson VM3 (2011)' equation in the Actilife software. This equation uses the vector magnitude to predict kcals (i.e., a combination of the three accelerometer planes). Additionally, the low frequency extension (LFE) option was selected at the download stage. This option lowers the baseband of the filter cut-off, expanding the bandwidth of the accumulated data. This was selected to ensure movement at the slow walking speeds was detected. The total EE value for the final 5 min of walking for each trial was divided by five to obtain a value for $\text{kcal}\cdot\text{min}^{-1}$. Steps were also calculated during the same min as the researcher-counted steps. The GT3X+ failed to collect data for three participants, leaving a final sample of 16 participants. The reason for the device malfunction is unclear.

Actiheart: Actiheart data were downloaded via a device docking station and processed using Actiheart software (CamNtech Ltd., Cambridge, UK). On attempting to download one participant's data it became evident that the Actiheart had failed to record any data, resulting in complete Actiheart data for 18 of the 19 participants. EE for the final 5 min of each trial was calculated using a branched modeling equation (labeled as *Group Cal JAP2007* in the software). This applied a flex heart rate algorithm for data below 25 accelerometer counts per min, and an alternate algorithm known as transition heart rate for data above 25 counts per min. This branched equation has been described in detail elsewhere (6). The branched model predicted EE in calories for the final five min of each walking trial. Total cal were divided by 1000 to achieve total kcal, and subsequently divided by five to achieve $\text{kcal}\cdot\text{min}^{-1}$.

Indirect calorimetry: $\dot{V}O_2$ and $\dot{V}CO_2$ values for the final 5 min of each walking trial were used to calculate $\text{kJ}\cdot\text{min}^{-1}$ using the Weir formula (24), which takes into account the energy derived from different fuel sources. The resulting value was multiplied by 0.238 to obtain $\text{kcal}\cdot\text{min}^{-1}$ (1). Body weight, height, and age were used to calculate resting metabolic rate (RMR) (12) for each participant. This RMR value was then subtracted from their total EE value for each walking trial, giving a final value for physical activity-related EE. $\text{Kcal}\cdot\text{min}^{-1}$ as determined by indirect calorimetry was used as the criterion value against which to compare GT3X+ and Actiheart estimates of EE.

Statistical Analysis

Descriptive statistics were calculated to characterize the sample and aspects of the treadmill walking trials. Pearson's product moment correlation *r* was calculated between measured EE values and EE estimates from each activity monitor. Data were combined across trials for correlational analyses. Repeated measures ANOVAs were used to investigate differences among measures for estimates of EE ($\text{kcal} \cdot \text{min}^{-1}$). Three ANOVAs were used (one for each walking trial). Fisher post-hoc pairwise comparisons were used to investigate differences between individual pairs of measures, adjusted using the Bonferroni method to control for multiple comparisons. Cohen's *d* was used to determine effect sizes (9). The same ANOVA analyses were used to investigate differences between researcher-counted steps and GT3X+ estimated steps (waist and wrist) for each walking trial. An adapted Bland Altman plot (14) with 95% limits of agreement was used to assess agreement between GT3X+ waist and GT3X+ wrist estimates of EE, pooled across walking trials. IBM SPSS Statistics (Version 20, IBM Corp., Armonk, NY.) was used for all analyses.

RESULTS

A total of 19 adults (mean age = 30 years, SD = 9) participated in the study. The average participant weight was 71.46 kg (SD = 10.55) and the average height was 174.37 cm (SD = 9.16). The mean walking speeds for each trial were: Slow = 2.59 km/hr (SD = 0.87), Medium = 3.74 km/hr (SD = 0.82), and Fast = 5.12 km/hr (SD = 0.81). Descriptive statistics for each outcome during the three trials are displayed in Table 1.

Significant positive correlations at the $p < .01$ level were found between indirect calorimetry estimates of EE and EE outputs from the GT3X+ waist ($r = .82$), the GT3X+ wrist ($r = .72$), and the Actiheart ($r = .77$). The omnibus ANOVA tests indicated significant differences among measures of EE for the slow (F (df = 3, 42) = 9.64, $p < .01$) and fast (F (df = 3, 42) = 26.42, $p < .01$) walking trials. There were no significant differences among measures of EE during the medium walking trial (F (df = 3, 42) = 2.42, $p > .05$). Pairwise differences between each device and EE from indirect calorimetry during the slow and fast trials are displayed in Table 2. The GT3X+ worn on the waist and wrist significantly underestimated EE during the slow walking trial, and significantly overestimated EE during the fast walking trial. EE estimates from the Actiheart were not significantly different than calorimetry measured EE for any trial.

The ANOVA results indicated that there were no significant differences among devices for step estimates during the slow walking trial (F (df = 1, 16) = 3.13, $p > .05$). Significant differences in step estimates were found among devices for the medium (F (df = 1, 20) = 8.96, $p < .01$) and fast (F (df = 1, 15) = 12.82, $p < .01$) walking trials. Post-hoc comparisons showed that in the medium and fast walking trials the GT3X+ worn on the wrist significantly underestimated steps. These differences were medium to large according to Cohen's *d*. Step estimates from the GT3X+ worn at the waist were not significantly different from researcher-counted steps for all trials. Details of the post-hoc comparisons for the medium and fast trials are displayed in Table 3.

An adapted Bland-Altman plot (Figure 1) was created to investigate agreement between waist- and wrist-worn GT3X+ determined EE, pooled across walking trials. Scores from the GT3X+ worn on the waist were plotted on the x axis because this is the device position typically used by

Table 1. Descriptive statistics for each walking trial

Trial	**Outcome**	**n**	**Mean**	**SD**	**Min.**	**Max.**	**Skew.**	**Kurt.**
Slow								
	Speed (Km/h)	19	2.59	0.87	1.1	4	-0.07	-0.84
	Counted steps	19	86	17	54	116	-0.13	-0.61
	GT3x+ waist steps	16	74	20	40	107	-0.04	-1.09
	GT3x+ wrist steps	16	80	16	52	107	-0.22	-.75
	Measured kcal $\cdot$min^{-1}	19	2.05	0.78	0.87	4.03	1.07	1.28
	GT3x+ waist kcal $\cdot$min^{-1}	16	1.17	1.21	0.00	3.64	0.89	-0.40
	GT3x+ wrist kcal $\cdot$min^{-1}	16	0.74	0.83	0.00	2.8	1.84	2.33
	Actiheart kcal $\cdot$min^{-1}	18	1.72	1.15	0.40	5.02	1.54	2.89
Medium								
	Speed (Km/h)	19	3.74	0.82	2	5.50	-0.13	0.36
	Counted steps	19	102	12	81	124	0.02	-0.52
	GT3x+ waist steps	16	97	10	80	116	-0.08	-0.26
	GT3x+ wrist steps	16	92	12	71	109	-0.12	-0.94
	Measured kcal $\cdot$min^{-1}	19	2.53	0.82	1.19	4.38	0.83	0.43
	GT3x+ waist kcal $\cdot$min^{-1}	16	3.04	1.77	0.2	6.12	-0.06	-0.53
	GT3x+ wrist kcal $\cdot$min^{-1}	16	2.59	1.62	0.12	5.02	0.15	-1.54
	Actiheart kcal $\cdot$min^{-1}	18	2.48	1.41	0.99	6.89	2.01	4.87
Fast								
	Speed (Km/h)	19	5.12	0.81	3.5	6.5	-0.51	-0.15
	Counted steps	19	116	10	98	136	0.28	-0.47
	GT3x+ waist steps	16	113	8	98	127	0.22	-0.34
	GT3x+ wrist steps	16	99	15	61	120	-1.08	1.55
	Measured kcal $\cdot$min^{-1}	19	3.55	1.18	1.54	6.01	0.79	0.39
	GT3x+ waist kcal $\cdot$min^{-1}	16	5.16	1.57	1.38	7.90	-0.74	1.50
	GT3x+ wrist kcal $\cdot$min^{-1}	16	4.14	1.19	2.32	6.22	-0.07	-1.21
	Actiheart kcal $\cdot$min^{-1}	18	3.41	1.74	1.22	8.94	2.04	5.59

Table 2. Differences between measured kcal $\cdot$min^{-1} and kcal $\cdot$min^{-1} estimates from each device.

Trial	Device	n	Mean diff.	*p*	*d*	95% CI
Slow						
	GT3X+ Waist	15	0.77	.04	0.76	0.04 – 1.51
	GT3X+ Wrist	15	1.22	< .01	1.58	0.45 – 1.99
	Actiheart	15	0.42	.36	0.51	-0.21 – 1.04
Fast						
	GT3X+ Waist	15	-1.90	< .01	-1.59	-2.77 - -1.04
	GT3X+ Wrist	15	-0.96	.02	-0.95	-1.77 - -0.14
	Actiheart	15	0.12	1.00	0.13	-0.45 – 0.70

Notes. d = Cohen's *d*, 95% CI = 95% confidence interval for difference

Table 3. Difference between researcher-counted steps/min and steps/min from each device.

Trial	Device	n	Mean diff.	*p*	*d*	95% CI
Medium						
	GT3X+ Waist	16	2	.32	0.20	-1.10 – 4.92
	GT3X+ Wrist	16	7	.02	0.63	1.18 – 13.07
Fast						
	GT3X+ Waist	16	1	.25	0.13	-0.29 – 1.56
	GT3X+ Wrist	16	14	< .01	1.25	3.80 – 24.40

Notes. d = Cohen's *d*, 95% CI = 95% confidence interval for difference

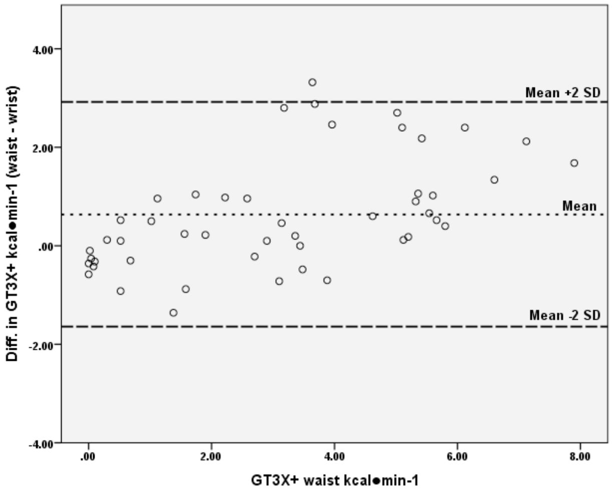

Figure 1. Adapted Bland Altman plot displaying agreement between GT3X+ waist and wrist EE estimates pooled across walking trials.

most researchers, not because we deemed it to be the criterion. Differences between measures (i.e., waist – wrist) were plotted on the y axis and 95% limits of agreement (mean difference ± 2 SD) were also added to the plot.

The Bland Altman plot indicates proportional bias, increasing at higher rates of EE. At EE rates above 4 kcal $\cdot$min^{-1}, the GT3X+ worn on the wrist appears to underestimate compared to when it is worn on the waist. This indicates a lack of agreement between device positions.

DISCUSSION

This study is the first to examine the accuracy of the Actigraph GT3X+ accelerometer for estimating EE in adults during walking, and to provide a comparison with the Actiheart activity monitor. EE is an important variable in the etiology of obesity, and therefore affordable accurate measurement instruments may permit a better understanding of the energy intake-expenditure relationship. Additionally, given that Actigraph Inc. is one of the primary producers of research-grade accelerometers, it is necessary to ensure that each new model provides trustworthy data for researchers interested in physical activity outcomes.

We found that EE estimates from the GT3X+ worn on the waist and wrist, and the Actiheart monitor correlate highly with EE measured by indirect calorimetry. These findings indicate good relative validity for the activity monitors (i.e. the monitors place participants in a similar order of EE as indirect calorimetry). Additionally, the GT3X+ worn on the wrist and waist provides accurate estimates of EE at medium walking speeds (i.e., 2 – 5.50 km/h), and can accurately determine steps at all walking speeds when worn on the waist. However, the GT3X+ underestimated EE during slow walking and overestimated EE during fast walking, when worn on both body positions. This suggests that there is not absolute agreement between GT3X+ EE estimates and measured EE across the continuum of walking speeds. The Freedson VM3 2011 equation used to calculate EE in the Actilife software was developed using a protocol that included walking and running (20). It has been shown that across a wide range of walking and running cadences, the cadence-EE relationship appears to be non-linear (18). Specifically, the cadence-EE relationship for walking constitutes a shallow linear relationship, whereas the relationship is steeper during running cadences. It is possible therefore, that the combination of walking and running used to develop the VM3 2011 equation applied to the data in the present study may partly, or entirely, account for the absolute differences in GT3X+ estimated EE and measured EE that we observed. Perhaps a more accurate approach would be to create EE algorithms that discriminate between walking and running, or account for the curvilinear nature of the cadence-EE relationship (for example by log-transforming the EE data). It should be noted that the discrete walking trials (i.e., slow, medium, and fast) that we used somewhat artificially grouped walking speeds together that are, in fact, part of a continuum. As such, there was a large overlap between the speeds from each trial, as can be seen in Table 1. The high linear relationship between GT3X+ estimated EE and calorimetry (comparable to the relationship for the Actiheart) indicates that with a relatively straightforward adjustment of the GT3X+ data-processing algorithms, accuracy might be achieved across the speed continuum.

We used the LFE option when downloading the GT3X+ data. This feature lowers the accelerometer baseband to include movements typically classified as being outside the normal range of human movement. Using this function should help to detect activity and steps at slower walking speeds or among individuals with non-normal walking gaits, such as the elderly. However, even with the LFE applied, the devices in our study underestimated physical activity EE at slow walking speeds. Steps were, however, accurately detected at the slow walking speeds when the device was worn on the waist. Researchers seeking to obtain conservative estimates of physical activity EE or who are interested in higher intensity activity may choose not to use the LFE, whereas those concerned about screeningout *bona fide* activity or who are interested in light intensity activity may wish to apply it. A study by Ried-Larsen et al (2012) is somewhat helpful in this regard. They found that GT3X+ output (activity counts) was higher when the LFE option was enabled compared to when it was disabled (16). Data were collected under both controlled mechanical and free-living conditions. However, in that study they only used this information to compare accuracy among different generations of Actigraph accelerometers, and did not establish which output (LFE enabled vs. disabled) was most similar to a known criterion.

An important finding from the present study is that when worn on the wrist, the GT3X+ is less accurate at determining steps than when worn on the waist. We found that the GT3X+ worn on the wrist did not accurately determine steps at medium and fast walking speeds, whereas steps were accurately estimated at all walking speeds when worn on the waist. Furthermore, poor agreement for EE estimates between waist- and wrist-mounted GT3X+ devices was exhibited by the adapted Bland Altman plot. The plot indicated that as the rate of EE increased, so did the rate of bias, such that the GT3X+ worn on the wrist systematically underestimated EE above a rate of 4 kcals$\cdot$min^{-1}. The reason for this underestimation when the GT3X+ is worn on the wrist may be related to the algorithm used to calculate EE. The Freedson VM3 2011 equation used in the Actilife software to calculate EE was developed using data from waist-worn devices (20). In order to calculate EE when the device is worn at the wrist, the Actilife software applies scaling to the accelerometer counts. These scaling values have yet to be validated, and may therefore contribute somewhat to the differences in output from waist- and wrist-worn devices. This is a particularly important finding given that the National Health and Nutrition Examination Survey (NHANES) will soon move to a wrist-mounted accelerometer protocol after several years of using a waist-mounted protocol (8). However, based on the findings of our study, this change in protocol will lead to a situation where previously collected data will not be comparable to future data, and may also lead researchers to conclude that activity levels are lower than they really are. Interestingly, our findings are consistent with those of Rowlands and Stiles (2012), who found that GT3X+ raw acceleration outputs during brisk walking were higher for waist-mounted GT3X+ devices than for those worn on the wrist. Similarly, they found no differences in output between device locations for slow walking. These findings were based on raw accelerometer values, and may therefore indicate that genuine differences in output exist between device locations, and differences may not be due to the scaling values that are applied at the data processing stage, as argued above.

Similar to previously conducted studies, we found that the Actiheart monitor provided accurate estimates of EE. This is unsurprising given that the Actiheart, in contrast to the GT3X+, uses combined accelerometer and heart rate data to provide EE estimates. Error associated with the movement-EE relationship is reduced by the inclusion of this heart rate data. Previous studies that have investigated Actiheart validity have found that it is a valid measure of movement, EE, and heart rate in several populations (5, 15, 22). In this regard, our study provides support for the continued use of the Actiheart in studies where EE is the primary outcome.

This study used a relatively small sample and did not include any free-living physical activities. Future studies should address these limitations. Additionally, future research should seek to develop EE prediction equations that account for the different relationships between walking and running cadences/speeds and EE. This may help to improve the accuracy of accelerometer-based activity monitors.

Accelerometers afford a more practical and cost-effective means of measuring EE compared to techniques such as indirect calorimetry or doubly labeled water. The Actigraph GT3X+ accelerometer correlates highly with measured EE when worn on the wrist and waist, and provides accurate estimates of steps during slow, medium, and fast walking when worn on the waist. However, the GT3X+ significantly underestimated EE during slow walking and overestimated EE during fast walking. Absolute differences observed between measured EE and GT3X+ estimated EE may be the result of systematic sources of bias that could be accounted for by adapting the algorithms that convert the acceleration signal to kcal. Researchers should be cautious about positioning devices on participants' wrists, as the resultant data are not comparable to that collected from waist-worn devices. The Actiheart provided accurate estimates of EE at slow, medium and fast walking speeds.

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