Summer 2021

Performance of the Wrist-worn Actigraph GT3X + in Measuring Physical Activity in Older Women

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Recommended Citation

Smith, M. T.(2021). *Performance of the Wrist-worn Actigraph GT3X + in Measuring Physical Activity in Older Women.* (Master's thesis). Retrieved from https://scholarcommons.sc.edu/etd/6427

PERFORMANCE OF THE WRIST-WORN ACTIGRAPH GT3X+ IN MEASURING PHYSICAL ACTIVITY IN OLDER WOMEN

by

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Bachelor of Science
Lindenwood University, 2018

Submitted in Partial Fulfillment of the Requirements

For the Degree of Master of Science in

Exercise Science

Arnold School of Public Health

University of South Carolina

2021

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ABSTRACT

Introduction: Being able to accurately measure physical activity intensity and energy expenditure is crucial to understanding the role physical activity plays in lowering the risk for disease. This thesis aims to examine the performance of the wrist-worn GT3X+ in measuring PAEE and classifying activity intensity in a healthy non-obese population of older women. Methods: Baseline data collected in the Women's Energy Expenditure in Walking Programs Study (ClinicalTrials.gov identifier: NCT01722136) were used. PAEE was measured concurrently for 2 weeks using the doubly labeled water method in combination with indirect calorimetry, the GT3X+ ActiGraph accelerometer (GT3X+, ActiGraph LLC, Pensacola, FL), and the SenseWear Armband Mini monitor (SWAM, BodyMedia Inc. Pittsburgh, PA, USA). Results: The GT3X+ showed a moderate correlation with the SWAM and DLW and IC in measuring PAEE. When estimating time spent in activity intensity, the GT3X+ underestimated sedentary time and overestimated activity intensity when compared to the SWAM. Furthermore, during the Epoch by Epoch analysis, the GT3X+ misclassified light intensity activity as MVPA 71.96% of the time. Conclusion: The currently available PAEE estimation equations do not allow us to accurately measure PAEE with the wrist-worn GT3X+ in a population of older women. Furthermore, when compared to the SWAM, the cut points available for the GT3X+ tend to overestimate time spent in light intensity activity and MVPA and underestimate sedentary time when worn on the wrist.

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LIST OF ABBREVIATIONS

CPM	Counts per Minute
EBE	Epoch by Epoch
EE	Energy Expenditure
IC	Indirect Calorimetry
PAEE	Physical Activity Energy Expenditure
REE	Resting Energy Expenditure
TDEE	Total Daily Energy Expenditure

CHAPTER 1

MANUSCRIPT

Introduction

Being able to accurately measure physical activity intensity and energy expenditure (EE) is crucial to understanding the role physical activity plays in lowering the risk for disease.[2-6] Indirect Calorimetry (IC) is used as a criterion method for measuring physical activity energy expenditure (PAEE) but due to the cumbersome nature of the equipment, is not a feasible option for measuring physical activity over long periods of time or under free-living conditions. The doubly labeled water method (DLW) is the gold standard method for measuring total EE,[7] however, its high cost limits its use in large studies. Furthermore, the DLW does not allow calculation of day-to-day PAEE and must be combined with another method in order to determine the average PAEE over a few days. Less expensive methods, like questionnaires, have shown poor validity when compared to criterion methods.[8]

Accelerometry is a widely used method of measuring sedentary time, physical activity, and EE because it poses many benefits over the aforementioned methods. Accelerometers are easy to use, low in cost when compared to the DLW and are more accurate than questionnaires or self-report measures.[9] Furthermore, they allow measurement of free-living EE, something that IC does not offer.[10] However, the validity of the available research grade accelerometers varies across brands, models, and placements,[11] The SenseWear Armband Mini (SWAM, BodyMedia Inc. Pittsburgh, PA, USA) monitor is a previously validated tri-axial accelerometer and multisensor monitor that provides estimates of PAEE, sedentary time, and active time. The SWAM is no longer being produced, therefore increasing the need for other valid and unobtrusive methods of estimating EE.

The GT3X+ ActiGraph accelerometer (GT3X+, ActiGraph LLC, Pensacola, FL) is a triaxial accelerometer that is commonly used to assess physical activity.[12] The GT3X+ is a small device that can be worn on the hip or the wrist. Several studies[13-15] have aimed to validate the GT3X+ for measuring PAEE when placed on the hip. These studies have shown acceptable validity, compared to IC, throughout a range of activity modalities and intensities (± 10% equivalence zone).[13] However, the placement presents challenges with under detection of activities with substantial arm movement.[14] However, the wrist placement may be the more comfortable placement for sleeping and daytime wear. Previous research has suggested that the wrist placement is effective in improving patient compliance.[16-19] A substantial improvement in compliance was seen in the 2011-2014 NHANES survey when the wrist placement was used as opposed to the 2003-2005 NHANES survey when the hip placement was used.[20] If the GT3X+ worn on the wrist proves to be a valid method of measuring PAEE and activity intensity, it would make it an ideal choice for many researchers.

Few studies have aimed to validate the wrist-worn GT3X+. One of these few was a study conducted by McMinn et al who aimed to determine the validity of GT3X+'s ability to estimate PAEE under controlled walking conditions. They found that PAEE estimates from the GT3X+ highly correlated with IC ($r = 0.72$). However, Bland-Altman plots revealed that the GT3X+ significantly underestimated PAEE during slow walking (mean difference of 1.22 kcal·min^{-1}) and significantly overestimated PAEE during fast walking (mean difference of 0.96 kcal·min^{-1}).[21] Hildebrand et al compared the raw accelerometer outputs of the GT3X+ from both the hip and wrist placement in 30 children and 30 adults during a range of activity intensities. For the purpose of developing regressing equations for estimating EE, VO_2 was measured by IC. Increases in VO_2 tended to correlate with an increase in output from both placements with the exception of a significantly lower output compared to VO_2 during a step activity in the protocol. ICCs between different placements of the GT3X+ was 0.905 with a CI of 0.903-0.907 in adults and 0.917 with a CI of 0.916-0.919 in children. Furthermore, the authors mention that taking into account the less obtrusive nature of the wrist placement, the ability to improve wear compliance makes the wrist placement a viable option.[22]

There is a lack of studies aiming to validate the GT3X+ in a population of non-obese older women. Therefore, this study aims to examine the performance of the wrist-worn GT3X+ in measuring PAEE and classifying activity intensity in a healthy non-obese population of older women. Specifically, we aimed to evaluate discrepancy and agreement of the wrist-worn GT3X+ in measuring PAEE and time spent in sedentary, light, and MVPA when compared to PAEE estimates from the SWAM and PAEE estimates derived from DLW-measured TDEE and IC-determined resting EE in a population of older women. Furthermore, we aimed to use epoch by epoch (EBE) analysis to quantify the discrepancies in activity intensity classification between the GT3X+ and the SWAM in a population of older women.

Methods

Baseline data collected in the Women's Energy Expenditure in Walking Programs (WeWalk) Study (ClinicalTrials.gov identifier: NCT01722136) were used for this study.[23,24] The WeWalk Study was a 16-week randomized controlled trial to investigate the effects of two different doses of moderate intensity exercise on energy expenditure in inactive older women. Study procedures were reviewed and approved by the University of South Carolina Institutional Review Board in Columbia, South Carolina. All participants signed a written informed consent prior to participation in the study.

Participants

Participant inclusion criteria included age (60-75years), body mass index (18-30kg·m^{-2}), self-reported stable weight ($\pm$ 3%) for the past three months, physically inactive (less than 20 min, 3 times per week of structured exercise) for the past three months, nonsmoking for the past year, and able to walk on a treadmill.[23,24] Exclusion criteria included self-reported serious cardiovascular, metabolic, or respiratory diseases, or other conditions that might affect protocol adherence, exercise safety, or be aggravated by exercise. Participants were also excluded if they were taking medications known to affect exercise performance or metabolism or reported excess caffeine use (>500mg·day^{-1}). A total of 87 women completed baseline measurements.

PAEE derived from TDEE determined by Doubly Labeled Water Method (DLW) and Resting Energy Expenditure (REE) determined by IC

The DLW procedure was published more in depth previously.[24] Briefly, the procedure included collecting urine samples over a 14-day period after participants consumed an oral dose of premixed $^{2}H_2{}^{18}O$. The enrichment of ^{18}O and ^{2}H in the urine samples was analyzed using the isotope ratio mass spectrometry, and TDEE was calculated following the standard procedures established at the Pennington Biomedical Research Center.

REE was measured on the last day of the DLW period after an overnight fast using IC performed under a ventilated hood. All measurements took place in the morning between 600 and 800h and at least 24 hours after the last bout of any structured exercise. The procedure was described previously.[24] To calculate PAEE, the thermic effect of food was assumed to account for 10% of TDEE.[25,26] PAEE was calculated as TDEE*0.9 – REE.

SenseWear Armband Mini (SWAM)

With the exception of during water activities, participants were instructed to wear the SWAM for the entire 14-day period that TDEE was measured by DLW. The SWAM was worn on the upper left arm, over the participants triceps. The manufacturer provided software (SenseWear Professional 8.0, BodyMedia, Inc.) was used to calculate EE and activity intensity for the SWAM. The software uses data from the monitor's sensors (heat flux, galvanic skin response, skin temperature, and near body ambient temperature) and individual information (age, sex, height, weight, smoking, and handedness) to give estimates of EE for each minute of wear time. EE estimates for each minute are then converted to METs which are then used to classify activity intensity. METs for sedentary, light, moderate, and vigorous activity are 1-1.5, 1.6-2.9, 3-5.9, and $\geq$ 6 METs respectively.[27]

ActiGraph GT3X+ (GT3X+)

The GT3X+ was worn on the non-dominant wrist during the same 14-day period TDEE was measured. Participants were instructed to wear the device for the entire 14-day period and to go about their normal weekly routines. The manufacturer provided software (ActiLife 6.9.5, ActiGraph, LLC) was used to calculate PAEE and activity intensity. Two different equations were used to calculate PAEE: *Freedson VM3 2011* (VM3) and *Freedson VM3 Combination 2011* (VM3 combo). A total of 3 sets of cut points were used to classify activity intensity: *Freedson Adult VM3 2011* (Freedson), *Keadle Women's Health VM 2014* (Keadle) and *Santos-Lozano Older Adults 2013*[28] (Santos) (Table 1). The Freedson and Keadle cut points were provided by the ActiLife Software while the Santos cut points were manually entered into the program. All cut points used were based on the 3-axis VM. Details of the cut points are listed in Table 1. To make comparison of cut points easier, Moderate, Vigorous, and Very Vigorous were combined into one category (MVPA). Minute-by-minute raw data were exported to Excel.

Statistical Analysis

PAEE Estimates, Time by PA Intensity, and CPM

Data from the GT3X+ and SWAM were compared and days with at least 22 hours of wear time for both monitors were included in the analysis. PAEE and time spent on specific PA intensity were tested for normal distribution. The PAEE variables that were not normally distributed were SWAM and VM3 while the PA intensity variables that were not normally distributed were SWAM MVPA and Keadle Light. Variables that were not normally distributed were used as the independent variable in the linear regression analyses. Pearson correlation (Spearman correlation for models with non-normal variables) and linear regression analyses were performed to assess the association of PAEE estimates between the GT3X+ and DLW and IC-determined PAEE and between GT3X+ and SWAM. PAEE determined by GT3X+ included the VM3 and VM3 combo equation. The same analyses were used to assess association of time estimates of activity intensities between the GT3X+ and the SWAM. Activity intensity determined by the GT3X+ included Freedson, Keadle, and Santos-Lozano cut points. Furthermore, we examined the associations of daily vector magnitude counts per minute (CPM) from the GT3X+ with PAEE estimates from the SWAM and DLW and IC. Spearman's correlation was used for CPM because the variable was not normally distributed. Intra Class Correlations (ICCs) were conducted to assess reliability using the two-way mixed model, single measures, and absolute agreement except for the CPM analysis in which consistency agreement was used. Bland-Altman plots were used to determine mean bias, trends, and the degree of agreement within the 95% confidence intervals of PAEE estimates between GT3X+ and DLW and IC-determined PAEE and between GT3X+ and SWAM, estimates of time in each intensity between the SWAM and the four different sets of GT3X+ cut points, and between GT3X+ CPM and DLW and IC-determined PAEE and SWAM PAEE. Analysis was performed using SAS OnDemand (SAS Institute, Cary, NC), except for analysis of ICCs which were ran in SPSS (version 20, Armonk, NY).

Epoch-by-Epoch (EBE) Analysis

The entire EBE analysis was performed in excel. All GT3X+ data were reintegrated into 60 second epochs in order to match the SWAM data. The Keadle cut points were chosen for this analysis because they provide estimates of sedentary time, making them more comparable to the SWAM. They were applied to the minute-by-minute GT3X+ data and each epoch was given a code to identify its activity intensity. Sedentary activity was coded as 0, light activity was coded as 1 and MVPA was coded as 2. The SenseWear software automatically coded each minute of wear by activity intensity based on METs. For each participant, the GT3X+ data were matched by time with the SWAM data. Times where data were available from both monitors were included in this analysis. For each epoch, the GT3X+ was evaluated on whether it agreed with the SWAM on activity intensity. The percent of epochs that agreed was calculated overall and for each of the activity intensities. Furthermore, we also evaluated where discrepancies between the two monitors lies. This was done by calculating what percentage of epochs did not agree and what intensity they were incorrectly classified as. This was done for each participant. Means and standard deviations for all participants were calculated for the following: overall agreement, sedentary agreement, light agreement, MVPA agreement, sedentary classified as light, sedentary classified as MVPA, light classified as sedentary, light classified as MVPA, MVPA classified as sedentary, and MVPA classified as light.

Results

Out of the 89 participants who provided baseline data, the mean age was 65.6 years and the mean BMI was 25.6 kg/m^2. The majority of participants were White/European American (84.3%) and completed 4 years or more of college (63.64%). Annual income ranged from $10,000-19,000 to $80,000+ with 44.58% of the women falling in the $80,000+ category. The majority of women were either employed for wages

(38.64%) or retired (51.14%). Over half of the women were married (64.77%) with the others being widowed, divorced, never married, or a member of an unmarried couple. Means and standard deviations for daily PAEE and time spent in activity intensities are shown in Table 2.

PAEE Estimates

Associations and ICCs between measures of PAEE are shown in Table 3. According to the linear regression models and correlations, the VM3 and VM3 combo equations showed similar results when compared to both the DLW method and the SWAM. Both correlations of VM3 and VM3 combo with DLW and IC-determined PAEE were greater than 0.50, indicating large effect size, while their correlations with SWAM-determined PAEE were moderate.

However, poor reliability for both equations when compared to the SWAM and even poorer when compared to DLW and IC were found, indicating poor resemblance of data between PAEE determined by GT3X+ (either equation) and the criterion measures (by SWAM and DLW and IC). The Bland-Altman plots in Figure 1 show large limits of agreement and an overestimation of PAEE when compared to DLW and IC, indicating poor agreement. Figure 2 also shows large limits of agreement for both equations when compared to the SWAM. Furthermore, when compared to the SWAM, the Freedson equations tend to overestimate PAEE at low levels of activity and underestimate PAEE at high levels of activity.

The supplemental table shows associations between SWAM and DLW and IC determined PAEE and SWAM and DLW TDEE. Furthermore, a supplemental figure shows Bland-Altman plots for the agreement between these measures. Agreement between the measures is much better for the measurement of PAEE than TDEE. Bland-Altman Plot A in the supplemental figure shows a smaller mean bias for estimation of PAEE between the two measures. However, plot A also shows a trend where the SWAM tends to overestimate PAEE at higher levels of activity. Plot B in the supplemental figure shows a similar trend, however, the mean bias is much larger for TDEE estimates between the two measures.

Time in Intensity

Associations and ICCs between estimates of time spent in activity intensity are seen in Table 4. The Keadle Women's Health VM cut points were the only cut points to produce estimates of Sedentary time while the other cut points only produced estimates of Light intensity activity and MVPA. Pearson's correlation and linear regression coefficients between Keadle sedentary time and SWAM sedentary time were high, while ICCs were low. A Bland-Altman plot for sedentary activity is shown in Figure 4. Large limits of agreement are seen along with a trend of consistently underestimating time spent in sedentary activity compared to SWAM.

As seen in Table 4, when estimating time spent in light intensity activity, the Keadle cut points performed better on the linear regression and correlation analyses because they were the only cut points to produce positive coefficients. Although the Keadle cut points performed better than the other cut points, the regression coefficients and correlation coefficients they produced would still be considered low. ICCs for Light intensity activity can also be seen in Table 4. Although, highest for the Keadle cut points, ICCS indicated poor reliability for all cut points when compared to the SWAM. Bland-Altman plots for light activity are shown in Figure 5. Again, the best agreement in measuring light intensity activity is seen between the two devices when the Keadle cut points are used.

All cut points produced similar estimates of time spent in MVPA. Therefore, no set of cut points outperformed another in regards to regression coefficients and Spearman’s correlations for time spent in MVPA when compared to the SWAM. As seen in Table 4, Spearman’s correlations for all cut points are high. Similarly, based on ICCs, no cut point seems to be largely outperforming the other in reliability of measuring MVPA. Bland-Altman plots for MVPA are shown in Figure 6. These plots show a trend of overestimating time spent in MVPA that strengthens as intensity level increases.

CPM

Associations and ICCs between CPM from the GT3X+ and PAEE determined by the SWAM and DLW and IC are shown in table 3. Higher regression coefficients were seen when CPM from the GT3X+ were compared to DLW and IC determined PAEE. Spearman’s correlation coefficients were greater than 0.60 when compared to both criterion measures. ICCs were also higher for consistency with DLW and IC determined PAEE, although only marginally. Bland-Altman plots for agreement of CPM with PAEE estimates from criterion measures are shown in figure 3. Figure 3a shows a lower mean bias compared to figure 3b, indicating better agreement of CPM and PAEE when compared to estimates from the SWAM.

Epoch-by-Epoch (EBE) Analysis

The Keadle cut points were chosen for the Epoch-by-epoch analysis because they showed the correct direction in correlation the with criterion measures and were the only cut points to offer estimations of sedentary time. As shown in table 5, the mean overall rate of agreement between the two devices was 52.07±6.4%. MVPA showed the highest rate of agreement of all the activity intensities with a mean agreement of 85.36±12.29%. Light intensity activity showed the poorest agreement rates with a mean of 25.19±7.90%. When the GT3X+ did not correctly identify light intensity activity, 71.96±10.25% of the epochs were classified as MVPA. The low agreement rates during light intensity activity and the misclassification of light intensity activity as MVPA indicate an overestimation of activity intensity of the GT3X+ when compared to the SWAM.

Discussion

To our knowledge, this study is the first to examine the performance of the wrist-worn GT3X+ in measuring PAEE in a healthy non-obese population of older women. Although the GT3X+ did not perform well when compared to the SWAM and DLW, our results are useful in informing future research and use of the GT3X+ accelerometer.

The two equations used to estimate PAEE from the GT3X+ were the VM3 and VM3 combo equations. The Bland-Altman plots between measures of PAEE indicated that the GT3X+ tended to overestimate PAEE at low levels of activity and underestimate PAEE at high levels of activity. However, the EE equations provided by ActiLife were developed for measuring PAEE from the hip. ActiLife provides an option for estimating PAEE from the GT3X+ when worn on the wrist but does not provide any validated EE equations. An equation that was developed for the wrist-worn GT3X+ may produce more accurate estimates of PAEE.

Only the Keadle cut points produced estimates for sedentary time. These estimates correlated well with the sedentary time estimated by the SWAM, but the Bland-Altman plot shows that the Keadle cut point consistently underestimates time spent in sedentary activity. In addition to this, the large limits of agreement also show poor agreement. These finding are contrary to ones found by Ellis et al. This study aimed to compare accuracy of behavior classifications made between the hip and wrist placement of the GT3X+. For seven days, participants wore two accelerometers (one on the hip and one on the wrist) and a camera that captured images every 20 seconds in order to attain information about true participant behavior. Chi-square tests ($p < 0.01$) were used to determine significant difference from true behavior. Both placements significantly overestimated time standing but estimated time sitting and riding in a vehicle were not significantly different from true behavior. Bland-Altman plots for minutes walking show no bias with increasing time for both the hip and wrist placement, indicating good agreement. The authors concluded that both placements provided accurate estimates of sedentary and walking minutes.[17] A reason for our contrary finding may be the device we chose as our criterion. We compared estimates of time in activity intensity to those from the SWAM while Ellis et al compared their estimates to direct observation of activity.

Because the Keadle cut points classified sedentary activity like the SWAM did, it was able to produce better estimates of light intensity activity than the rest of the cut points. The correlation and linear regression analysis showed that all cut points were not strongly associated with the SWAM when measuring light intensity activity. However, the Keadle cut points show the smallest limits of agreement and lowest mean bias by the Bland-Altman plots (Figure 5) compared to the other cut points, indicating the best agreement with the SWAM on light intensity activity. The Keadle cut points may have showed the best agreement with the SWAM because it classified sedentary activity separately while the other cut points did not. Because the SWAM also classified sedentary activity separately, it makes sense why the Keadle cut points would produce the most accurate estimates when compared to the SWAM.

All cut points produced similar estimates of MVPA. Spearman's correlations for MVPA between all cut points and the SWAM were moderate, while regression coefficients were close to 2. A linear regression coefficient close to 2 indicates that the GT3X+ was overestimating time spent in MVPA at a rate of 2 to 1 when compared to the SWAM. ICCS showed poor reliability and Bland-Altman plots in figure 6 showed that all cut points overestimate time spent in MVPA and the overestimation increases at higher levels of intensity. Furthermore, the plots show a large mean bias and limits of agreement. All of this indicates poor reliability between the two devices. An overestimation of time spent in MVPA may be explained by an overestimation of PAEE which has been seen in other studies aiming to validate the GT3X+.

A study that saw an overestimation of PAEE at higher intensities was one conducted by McMinn et al who aimed to determine the validity of GT3X+'s ability to estimate PAEE under controlled walking conditions and examined the agreement between the hip and wrist placements. A total of 19 participants, aged 19-53 years old, completed three walking trials: a slow-walking trial, a medium-walking trial, and a fast-walking trial. The study compared PAEE estimates from the GT3X+ to indirect calorimetry (IC) and found that PAEE estimates from the GT3X+ highly correlated with IC (hip: r = 0.82, wrist: r = 0.72). However, Bland-Altman plots revealed that the GT3X+ (hip and wrist) significantly underestimated PAEE during slow walking (mean difference of 0.77 and 1.22 for hip and wrist respectively) and significantly overestimated PAEE during fast walking (mean difference of -1.9 and -0.96 for hip and wrist respectively). No differences were seen between the hip and wrist placements during the medium walking trial. McMinn ultimately concluded that the GT3X+ shows high correlation with IC measured PAEE but poor agreement during slow and fast walking trials, and when worn on the wrist, the GT3X+ tended to underestimate EE at rates above 4 kcal·min^{-1}.[21]

For the EBE analysis, the mean overall agreement between the two monitors was 52.07%, with the highest agreement rate happening during the measurement of MVPA (85.36%). However, when measuring light intensity activity, the GT3X+ performed very poorly when compared to the SWAM (25.19% agreement). Furthermore, the analysis revealed that the GT3X+ tends to overestimate light intensity activity when compared to the SWAM, misclassifying light intensity activity as MVPA 71.96% of the time. This discrepancy may be due to the tendency of the GT3X+ to overestimate activity intensity and underestimate sedentary time. This would also explain the high agreement rate with the SWAM for MVPA. The results of our EBE analysis are consistent with the results of our analysis of time spent in activity intensity. Bland-Altman plots in figure 5 showed that all GT3X+ cut points overestimate time spent in MVPA which can be explained by an overestimation of PAEE that has been seen in the previously mentioned studies.[14,21] Agreement between the two devices on sedentary activity was similar to the overall agreement, with an average of 57.07% of the epochs between the two devices agreeing when the SWAM classified activity as sedentary.

CPM from the GT3X+ were compared to PAEE estimates from the SWAM and DLW and IC. Spearman correlations between CPM from the GT3X+ and criterion measures were moderate. These results indicate that a more accurate estimation of PAEE from the wrist-worn GT3X+ is possible and the problem may lie in the estimation equations. Results of other studies looking at CPM suggest this as well. One study found a Pearson's correlation of 0.88 between CPM from the wrist-worn GT3X and the hip worn GT3X.[29] If wrist-worn CPM are strongly correlated with hip worn CPM, it should be possible to get similar estimates of PAEE from both placements. This is significant because the hip placement of accelerometers has been previously validated.[10,11,13,30]

Findings by Shiroma et al can help to explain the overestimation of PAEE and activity intensity that we saw in our study. Shiroma et al examined how wear placement of the GT3X+ would affect accelerometer output. The GT3X+ was worn on each wrist along with one on the hip for 7 days. During this time, the devices worn on the wrist produced significantly higher CPM than the device worn on the hip.[31] Since CPM are used to calculate PAEE and activity intensity, and the equations are developed for the hip placement, a higher CPM from the wrist placement would explain the overestimation of PAEE and activity intensity.

Strengths of this study include the use of DLW and lab measured REE as a criterion measure since it is considered the gold standard in techniques measuring EE. Other strengths include objectively determined PA and sedentary time, long wear time of the activity monitors each day, the number of days the women wore the activity monitors, and matching monitor wear time and DLW measurement period.[27]

Although this study has many strengths, several limitations should be considered. REE was only measured once and was used as a representation of the individuals average REE. Most importantly, the participants enrolled in the study were non-obese inactive older women and it is well known that the validity of accelerometry algorithms may be affected by age and activity level. Therefore, the results of this study cannot be generalized to populations outside of this study sample.

Conclusion

In conclusion, the currently available PAEE estimation equations do not allow us to accurately measure PAEE with the wrist-worn GT3X+ in a population of older women. Furthermore, when compared to the SWAM, the cut points available for the GT3X+ tend to overestimate time spent in light intensity activity and MVPA and underestimate sedentary time when worn on the wrist. This is most likely due to the fact that there are few PAEE equations and intensity cut points developed for the device when worn on the wrist and none that fit our participant demographic. Future research should explore the validity of the wrist-worn GT3X+ in different populations and work to develop EE equations for the wrist placement.

Table 1.1 Cut Points Used for Estimation of Activity Intensity

Cut Point	Short name	Sedentary	Light	Moderate	Vigorous	Very Vigorous
Freedson Adult VM3 2011	Freedson		0-2689	2690-6166	6167-9642	9643 +
Keadle Women's Health VM 2014	Keadle	0-199	200-2689	2690 +		
Santos-Lozano Older Adults 2013	Santos		0-2750	2751-9359	9360 +	

Values represent vector magnitude counts per minute.

Table 1.2 Descriptive Statistics of Measures

Measures	*n*	Mean ± SD
PA Energy Expenditure (kilocalories/day)		
SWAM	87	1160.1±1088.1
DLW and IC-derived	72	630.7±202.1
GT3X+ (VM3)	87	1414.4±509.8
GT3X+ (VM3 Combo)	87	1552.8±509.3
Vector Magnitude Counts per Minute (CPM)		
GT3X+	87	1591.1±501.5
Sedentary Time (minutes/day)		
SWAM	85	1116.1±120.5
GT3X+ (Keadle)	85	866.3±110.5
Time in Light Intensity (minutes/day)		
SWAM	85	261.7±103.1
GT3X+ (Freedson)	85	1130.5±85.8
GT3X+ (Keadle)	85	264.2±50.1
GT3X+ (Santos)	85	1138.6±84.8
Time in MVPA (minutes/day)		
SWAM	85	39.1±27.0
GT3X+ (Freedson)	85	308.2±87.1
GT3X+ (Keadle)	85	308.2±87.1
GT3X+ (Santos)	85	300.2±86.1

Table 1.3 Associations and ICCs between Measures of PAEE

Independent Variable	Dependent Variable	n	Regression coefficients	P-value	r	ICCs
SWAM	VM3	85	0.15 (0.06, 0.25)	0.0024	0.413*	0.240 (0.038, 0.425)
SWAM	VM3 combo	85	0.16 (0.06, 0.26)	0.0015	0.400*	0.235 (0.035, 0.420)
DLW and IC	VM3	70	1.23 (0.72, 1.75)	<0.001	0.564*	0.112 (-0.072, 0.338)
DLW and IC	VM3 combo	70	1.21 (0.70, 1.72)	<0.001	0.501	0.088 (-0.060, 0.293)
SWAM	CPM	85	0.18 (0.09, 0.28)	0.0002	0.608*	0.303 (0.097, 0.484)
DLW and IC	CPM	70	1.26 (0.74, 1.78)	<0.0001	0.625*	0.349 (0.125, 0.538)

Data presented as regression coefficient (95% CI) and ICCs (95% CI). *Indicates Spearman correlation.

Table 1.4 Associations and ICCs between Measures of Time in Intensity

Independent Variable	Dependent Variable	n	Regression Coefficients	P-value	r	ICCs
Sedentary						
SWAM	Keadle	85	0.65 (0.50, 0.79)	<0.001	0.705	0.211 (-0.053, 0.551)
Light						
SWAM	Freedson	85	-0.58 (-0.71, -0.45)	<0.001	-0.701	-0.016 (-0.020 0.020)
SWAM	Keadle	85	0.15 (0.05, 0.25)	0.0037	0.329*	0.247 (0.035, 0.437)
SWAM	Santos	85	-0.57 (-0.70, -0.44)	<0.001	-0.697	-0.016 (-0.019, 0.020)
MVPA						
SWAM	Freedson	85	2.08 (1.55, 2.62)	<0.001	0.676*	0.038 (-0.026 0.154)
SWAM	Keadle	85	2.08 (1.55, 2.62)	<0.001	0.676*	0.038 (-0.026, 0.154)
SWAM	Santos	85	2.07 (1.54, 2.60)	<0.001	0.675*	0.039 (-0.027, 0.160)

Data presented as regression coefficient (95% CI) and ICCs (95% CI). *Indicates Spearman Correlation.

Table 1.5 Epoch by Epoch Analysis of Agreement with SWAM (criterion)

	Mean	SD	CI
Overall agreement	52.07%	6.40%	(50.68% - 53.46%)
Sedentary agreement	57.07%	7.07%	(55.54% - 58.60%)
Light agreement	25.19%	7.90%	(23.48% - 26.91%)
MVPA agreement	85.36%	12.29%	(82.69% - 88.03%)
Sedentary classified as light	32.40%	4.55%	(31.41% - 33.39%)
Sedentary classified as MVPA	10.53%	4.43%	(9.57% - 11.49%)
Light classified as sedentary	2.84%	3.53%	(2.08% - 3.61%)
Light classified as MVPA	71.96%	10.25%	(69.74% - 74.19%)
MVPA classified as sedentary	0.84%	2.01%	(0.41% - 1.28%)
MVPA classified as light	13.80%	11.44%	(11.31% - 16.28%)

Agreement is defined as incidences where the GT3X+ classified activity intensity correctly when compared the SWAM (criterion).

Table 1.7 Supplemental Table: Associations of PAEE and TDEE determined by Criterion Measures

Independent Variable	Dependent Variable	n	Regression coefficients	P-value	r	ICCs
PAEE						
SWAM	DLW	71	0.05(0.009-0.089)	0.0170	0.413*	0.076 (-0.107 – 0.270)
TDEE						
SWAM	DLW	70	0.21(0.16-0.26)	<0.001	0.698*	0.010 (-0.007-0.047)

Data presented as regression coefficient (95% CI) and ICCs (95% CI). *Indicates Spearman correlation.

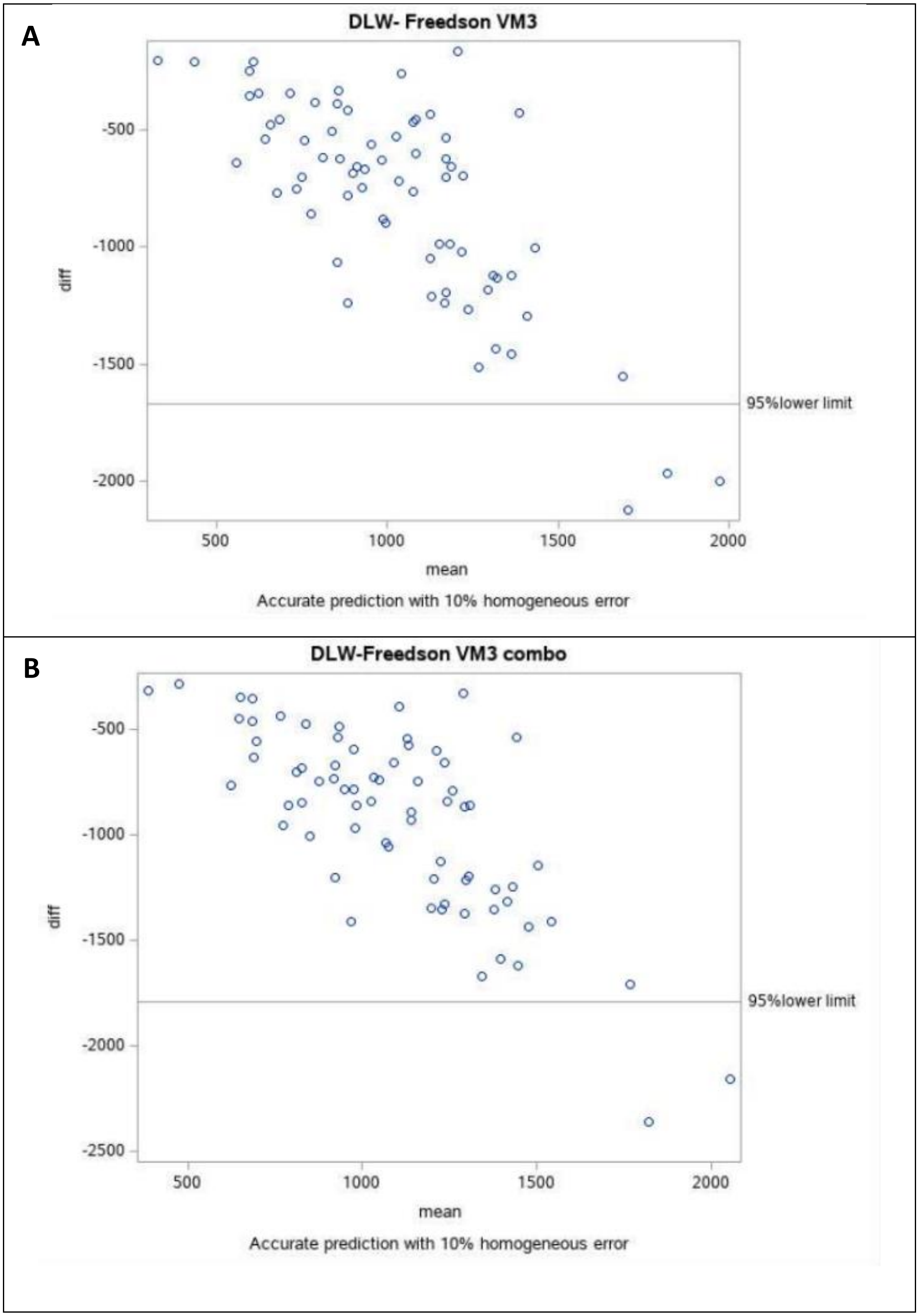

Figure 1.1 Bland-Altman plot for agreement of PAEE estimates between DLW and IC (criterion) and the *Freedson VM3 2011* equation and *Freedson VM3 combination 2011* equations. Data presented as difference in kilocalories between criterion and GT3X+.

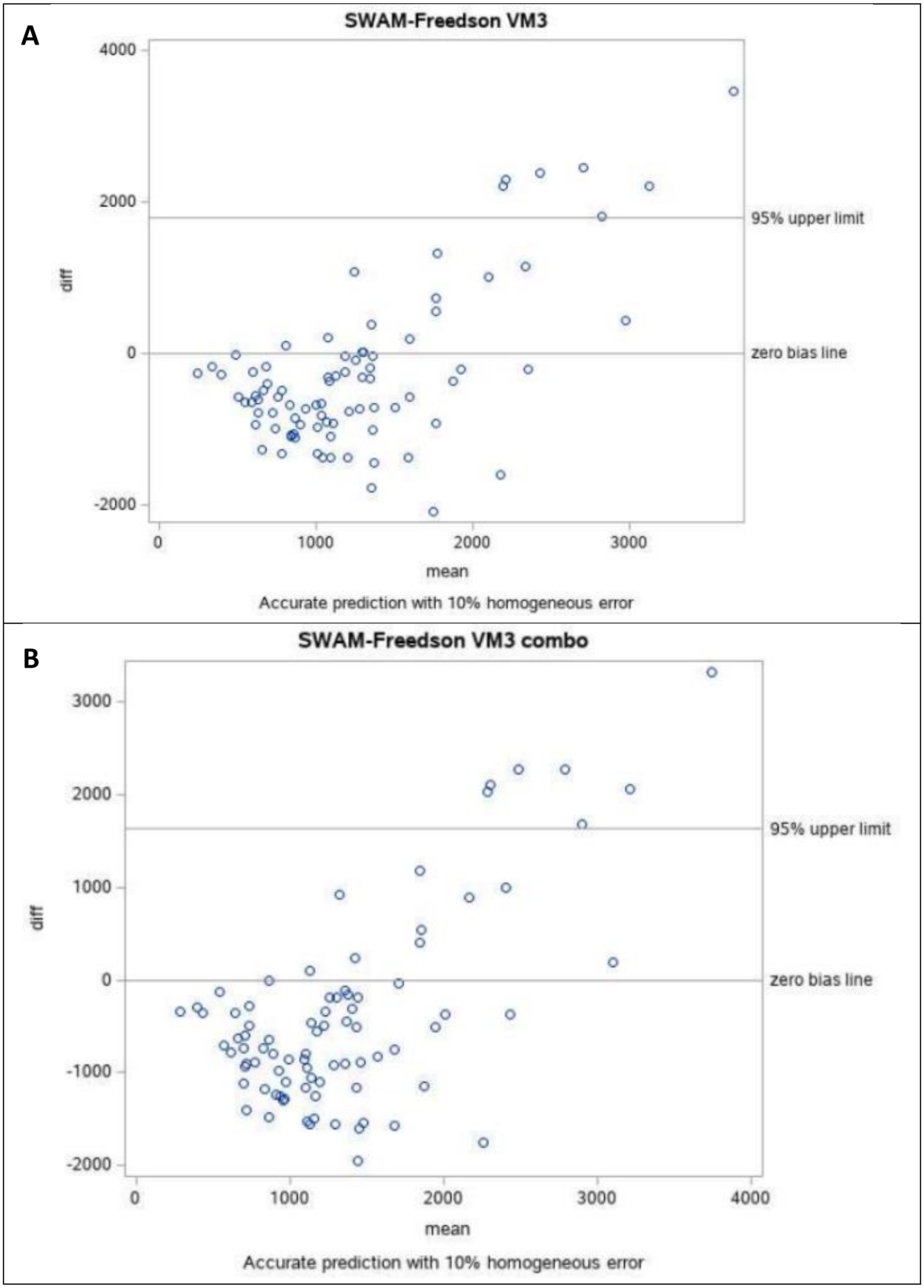

Figure 1.2 Bland-Altman plot for agreement of PAEE estimates between SWAM (criterion) and the *Freedson VM3 2011* equation and *Freedson VM3 combination 2011* equations. Data presented as difference in kilocalories between criterion and GT3X+.

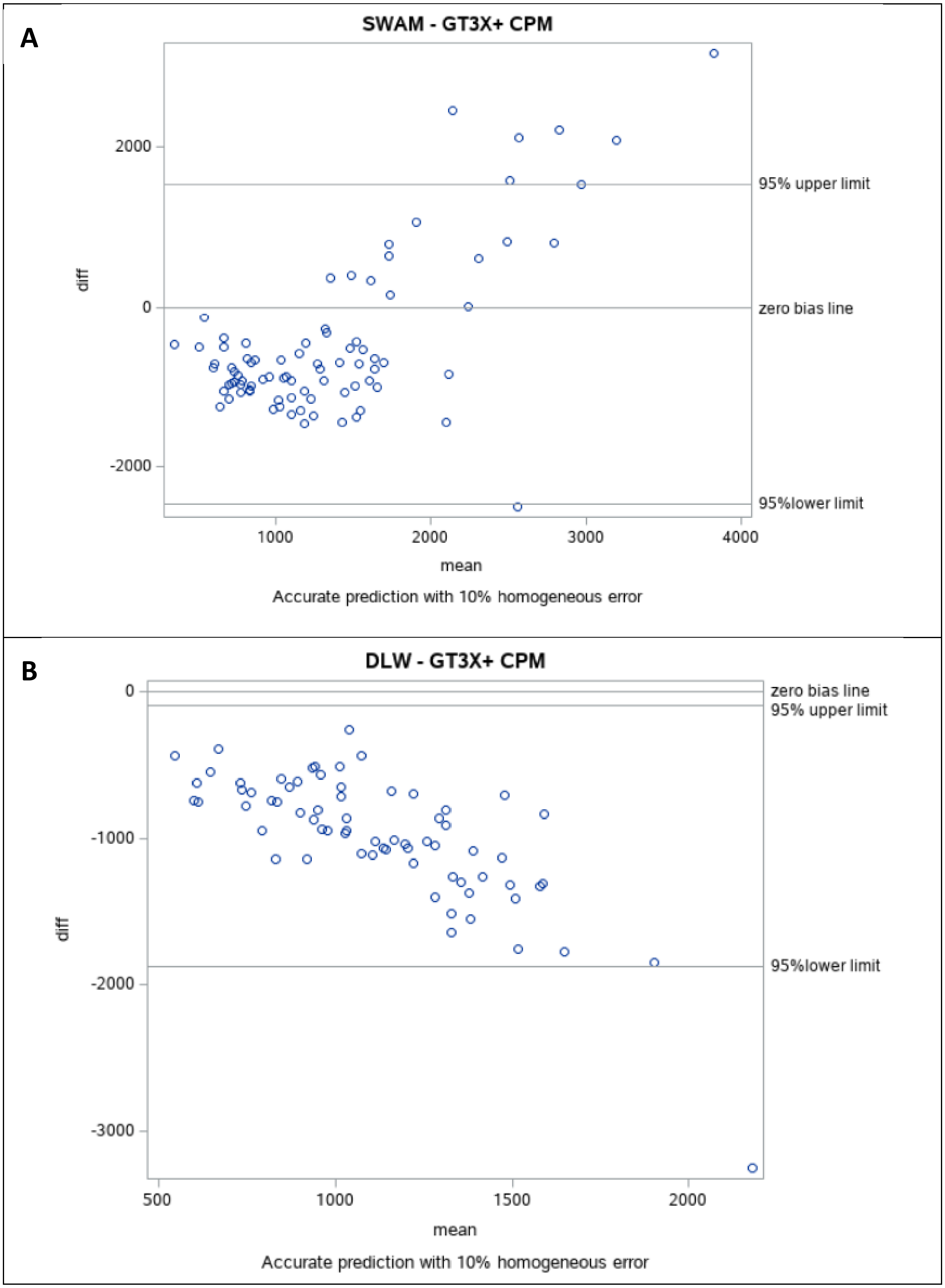

Figure 1.3 Bland-Altman plot for agreement of CPM with estimates of PAEE from SWAM and DLW and IC. Data presented as difference between criterion measured PAEE and GT3X+ CPM.

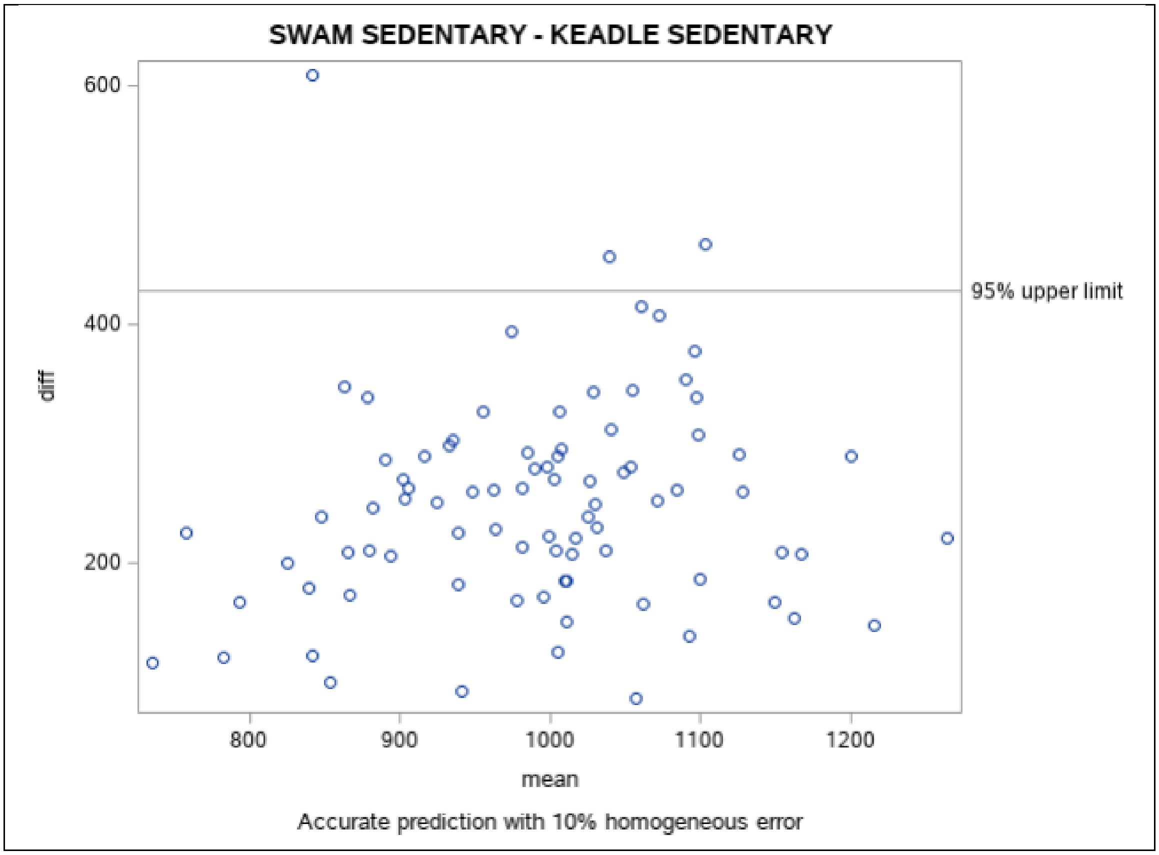

Figure 1.4 Bland-Altman Plot for Time Spent in Sedentary Activity Compared to Criterion (SWAM). Data presented as difference in minutes between SWAM and GT3X+.

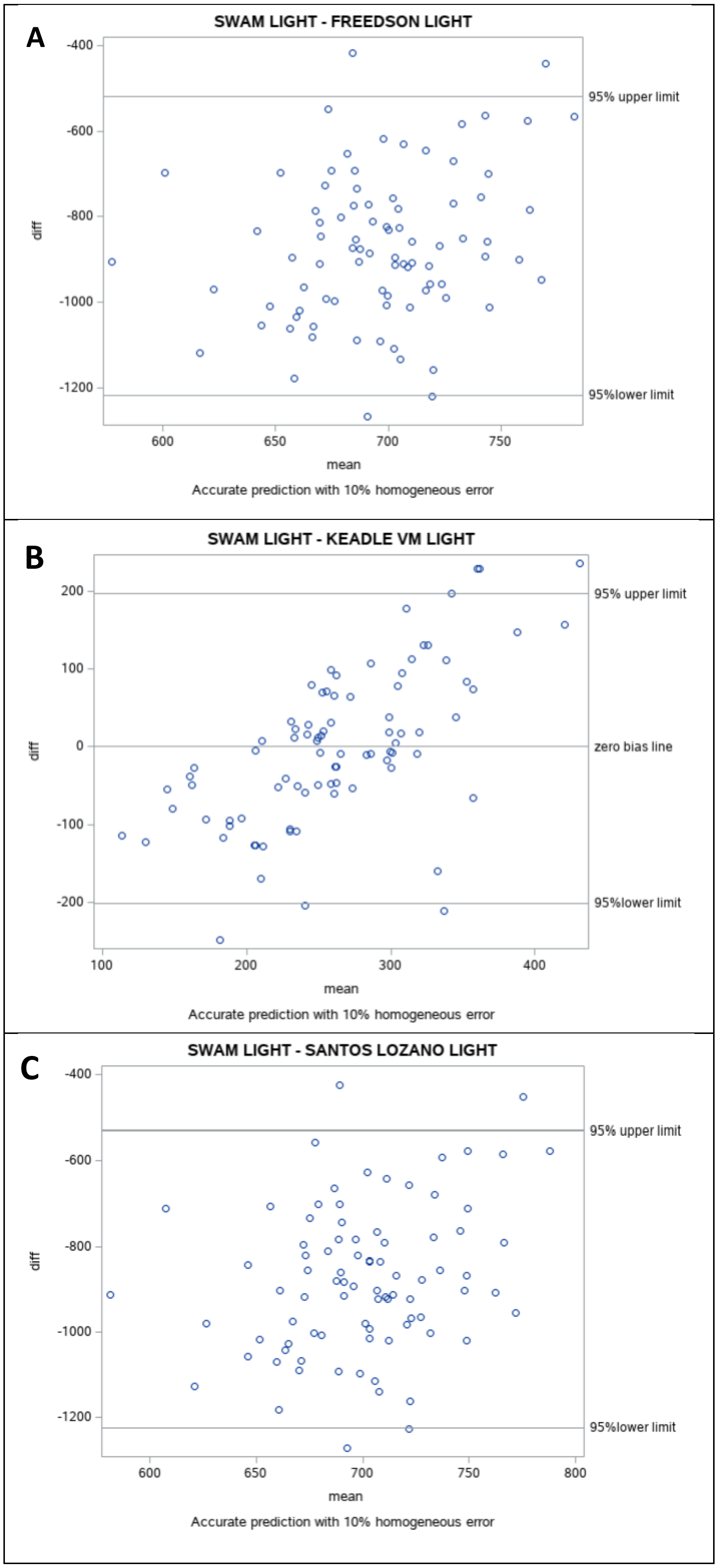

Figure 1.5 Bland-Altman's for Time Spent in Light Activity Compared to Criterion (SWAM). Data presented as difference in minutes between SWAM and GT3X+.

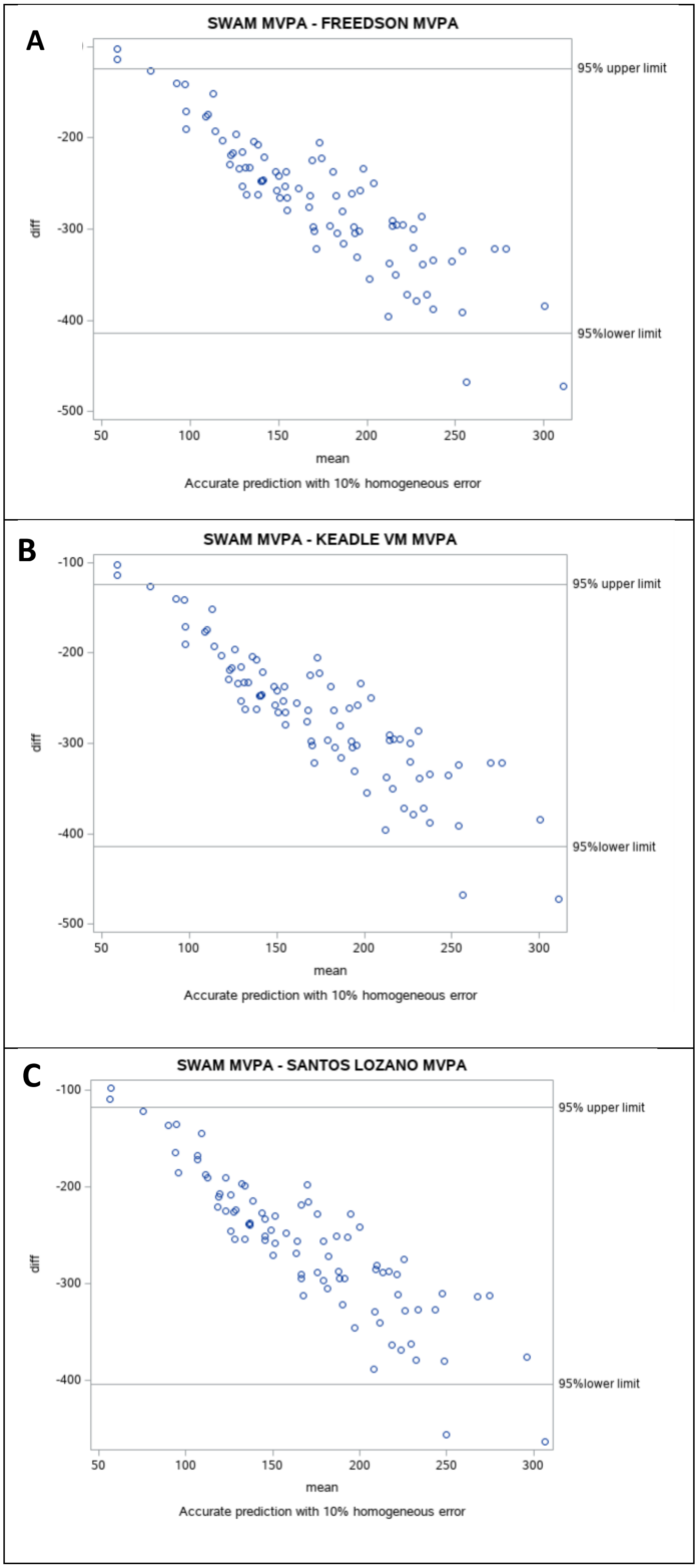

Figure 1.6 Bland-Altman's for Time Spent in MVPA Compared to Criterion (SWAM)Data presented as difference in minutes between SWAM and GT3X+.

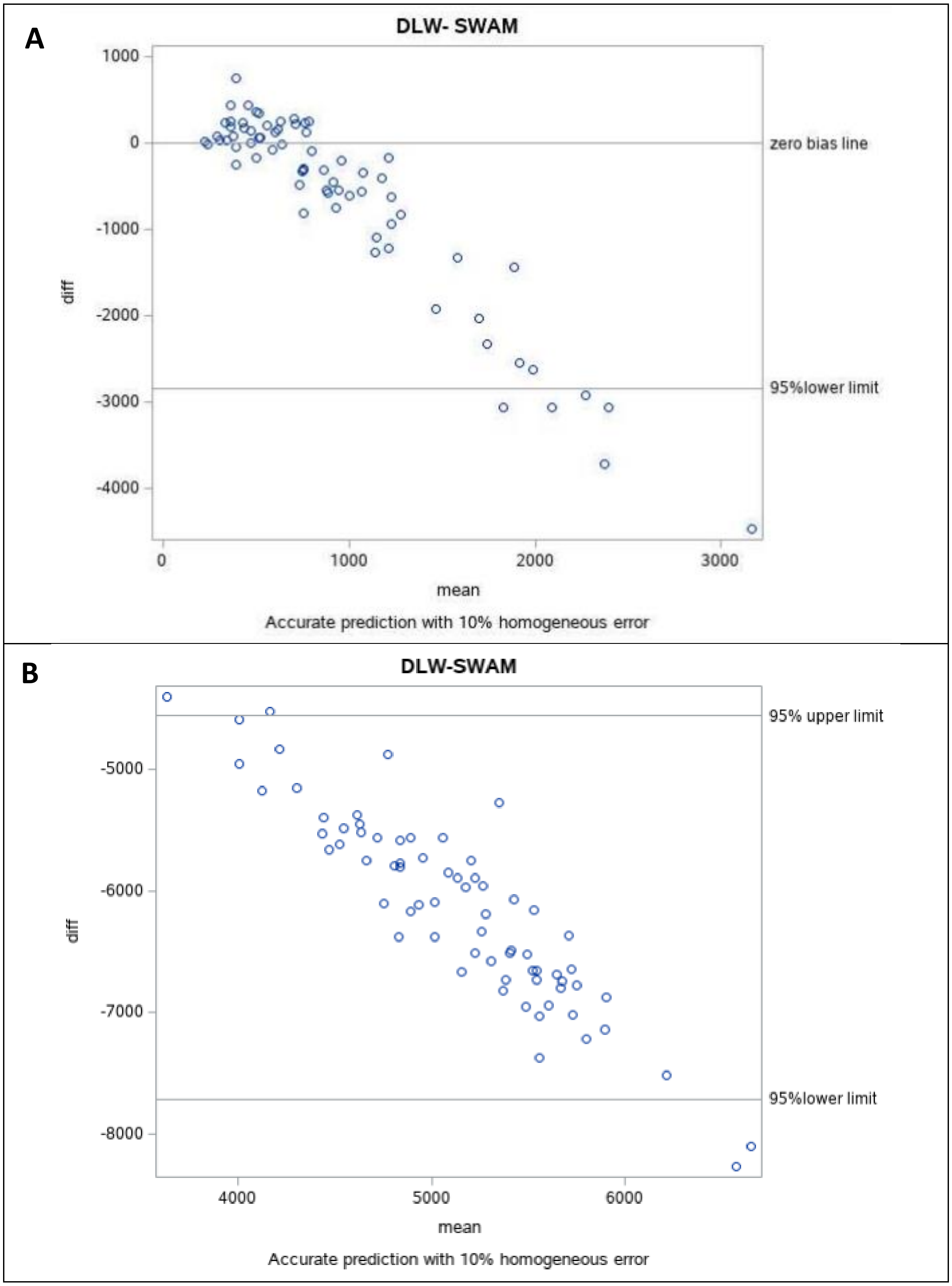

Figure 1.7 Supplemental Figure: Bland-Altman plot of agreement between criterion measures of PAEE and TDEE. A: agreement of PAEE estimates. B: agreement of TDEE estimates.

CHAPTER 2

THESIS PROPOSAL

A common way to measure physical activity and physical activity energy expenditure (PAEE) is through accelerometry. Accelerometers can be defined as devices that measure body acceleration (speed in respect to time), which is then used to estimate physical activity intensity over time. Therefore, accelerometry is based on the assumption that the body's acceleration is relative to the muscular force behind the acceleration and thus relative to the EE of the movement.[32] Due to the strong relationship between physical activity and chronic disease, accurate measurement of physical activity intensity and EE is crucial to understanding the role physical activity plays in lowering the risk for chronic diseases like diabetes, cardiovascular disease, and cancer.[1-6] Accelerometry is a widely used method of measuring sedentary time, physical activity, and EE. Its relatively low cost, ease of use, unobtrusive nature, and ability to record continuous data for long periods of time make it an ideal choice for research.[10]

EE can be defined as the amount of energy in the form of calories a person uses.[33] Total daily energy expenditure (TDEE) is the total amount of calories a person expends in a day and is made up of three components: PAEE, the thermic effect of food (TEF), and resting metabolic rate (RMR).[33] An increase in PAEE may lead to many positive health outcomes. However, being able to accurately measure PAEE in free-living individuals still proves difficult despite its necessity.

The Doubly labeled water method (DLW) is the gold standard method for measuring TDEE.[7] PAEE can be determined from the DLW-determined TDEE by subtracting TEF and RMR. Although this method is highly accurate, its high cost and time-consuming methods limit its use in large studies.[32,34] Furthermore, the DLW does not allow calculation of day-to-day TDEE and instead provides mean energy expenditure (EE) estimates for the entire measurement period.[11] Indirect Calorimetry (IC) is also used as a criterion method for measuring PAEE but due to the cumbersome nature of the equipment, is not a feasible option for measuring physical activity over long periods of time or under free-living conditions. Less expensive methods, like questionnaires, have shown poor validity when compared to DLW.[8]

Accelerometry is a widely used method of quantifying EE because it poses many benefits over the aforementioned methods. Accelerometers are low in cost when compared to the DLW and are more accurate than questionnaires or self-report measures. Furthermore, they allow measurement of free-living EE, something that IC does not offer.[10] Accelerometry is widely used in activity and obesity research because of the insight it gives into individual’s activity levels as well as the body’s metabolic and physiological changes. However, the validity of the available research grade accelerometers varies across brands, models, and placements.[11] Therefore, there is a substantial need for valid accelerometers in the field.

The SenseWear Armband Mini (SWAM) monitor is a previously validated tri-axial accelerometer and multisensor monitor that provides estimates of PAEE, sedentary time, and active time. The SWAM is worn on the participant’s upper arm and is relatively small compared to previous versions. The SWAM is no longer being produced, therefore increasing the need for other valid and unobtrusive methods of estimating EE.

The GT3X+ ActiGraph accelerometer (GT3X+, ActiGraph LLC, Pensacola, FL) is a triaxial accelerometer that is commonly used to assess physical activity.[12] The GT3X+ is a small device that can be worn on the hip or the wrist. Several studies[13-15] have aimed to validate the GT3X+ for measuring PAEE when placed on the hip. However, the wrist placement may be the more comfortable placement for sleeping and daytime wear since many people are accustomed to wearing a watch. Previous research has suggested that unobtrusive devices that integrate measurement into devices already accepted by a large number of people are effective in improving patient compliance.[16-19] Based on this theory, the wrist placement of the GT3X+ may create less participant burden than the hip placement since it is similar to wearing a watch, which many individuals do already. A substantial improvement in compliance was seen in the 2011-2014 NHANES survey when the wrist placement was used as opposed to the 2003-2005 NHANES survey when the hip placement was used.[20] Despite this, little is known about the validity of the GT3X+ in measuring PAEE when worn on the wrist. If the GT3X+ worn on the wrist proves to be a valid method of measuring EE, it would make it an ideal choice for many researchers. To our knowledge, this study is the first to examine the ability of the wrist-worn GT3X+ to accurately measure PAEE in a healthy non-obese population of older women.

Purpose

Therefore, the purpose of this thesis is to evaluate the performance of the wrist-worn GT3X+ to estimate PAEE and classify activity intensity when compared to PAEE determined by DLW and indirect calorimetry and to the previously validated SWAM monitor. The specific aims of this thesis are outlined below.

Aim 1: To evaluate discrepancy and agreement of the wrist-worn GT3X+ ActiGraph accelerometer (GT3X+, ActiGraph LLC, Pensacola, FL) in measuring PAEE and time spent in sedentary, light, and moderate to vigorous physical activity when compared to PAEE estimates from the Sense Wear Armband Mini monitor (SWAM, BodyMedia Inc. Pittsburgh, PA, USA) and PAEE estimates derived from DLW measured TDEE and IC in a population of older women.

Aim 2: To use epoch by epoch analysis to quantify the discrepancies in activity intensity classification lie between the GT3X+ and the SWAM in a population of older women.

Hypothesis

The GT3X+ worn on the wrist will produce comparable estimates of PAEE when compared to the DLW and IC, and the previously validated SWAM monitor. Furthermore, estimations of time spent in sedentary, light, moderate, and vigorous activity from the GT3X+ and the SWAM will be similar.

Methods

Baseline data collected during the Women's Energy Expenditure in Walking Programs (WeWalk) Study (ClinicalTrials.gov identifier: NCT01722136) will be used for this thesis.[23,24] The WeWalk Study consisted of a 16-week randomized control trial to investigate the effects of two different doses of moderate intensity exercise on energy expenditure in inactive older women. Study procedures were reviewed and approved by the University of South Carolina Institutional Review Board in Columbia, South

Carolina. All participants signed a written informed consent prior to participation in the study.

Participants

Participant inclusion criteria included age (60-75years), body mass index (18-30kg*m^{-2}), self-reported stable weight (± 3%) for the past three months, physically inactive (less than 20 min, 3 times per week of structured exercise) for the past three months, nonsmoking for the past year, and able to walk on a treadmill.[23,24] Exclusion criteria included self-reported serious cardiovascular, metabolic, or respiratory diseases, or other conditions that might affect protocol adherence, exercise safety, or be aggravated by exercise. Participants were also excluded if they were taking medications known to affect exercise performance or metabolism or reported excess caffeine use (>500mg*day^{-1}). A total of 87 women completed baseline measurements. This thesis will use data obtained during baseline measurements.

TDEE determined by Doubly Labeled Water Method (DLW)

The DLW procedure was published previously.[24] The DLW was used over a 14-day period to measure TDEE. At baseline on day 1 a urine specimen was obtained after an overnight fast. Afterwards, an oral dose of premixed $^{2}H_2{}^{18}O$, adjusted to the participants body weight, was administered. To ensure participants received the entire dose, the dosing cup was rinsed twice with regular water and consumed following the consumption of the $^{2}H_2{}^{18}O$. The second and third urine samples were collected one hour apart from each other on the morning of day 2. Two more urine samples were collected on the morning of day 15 to close the measurement period. The collection time of each sample was recorded. Urine samples were stored at a temperature of -80°C. Samples were analyzed in batches and the enrichment of ^{18}O and ^{2}H was analyzed using the isotope ratio mass spectrometry. TDEE was calculated following the standard procedures established at the Pennington Biomedical Research Center. The thermic effect of food was assumed to account for 10% of TDEE.[25,26]

Resting Metabolic Rate (RMR)

RMR was measured on the last day of the DLW period after an overnight fast using IC performed under a ventilated hood. All measurements took place in the morning between 600 and 800h and at least 24 hours after the last bout of any structured exercise. After resting for 15 min upon arrival, participants remained awake, motionless, and in a supine position in a quiet room for the assessment. Data collection was 30 min in duration. The expired air was collected through a one-way valve and analyzed using a metabolic cart (TrueOne 2400, ParvoMedics, Salt Lake City, UT), which was calibrated the morning prior to the measurement. To avoid unstable measurements, the first and last 5 min of data were excluded. Using Weir's (1949) equation, RMR was calculated from each value of VO_2 and VCO_2.[24]

ActiGraph GT3X+ (GT3X+)

The GT3X+ was worn on the non-dominant wrist during the same 14-day period TDEE was measured. Participants were instructed to wear the device for the entire 14-day period and to go about their normal weekly routines. The manufacturer provided software (ActiLife 6.9.5, ActiGraph, LLC) will be used to calculate physical activity, sedentary time and PAEE using the *Freedson VM3 2011, Freedson VM3 Combination 2011 and Crouter adult 2010* cut points provide by the software. Cut points derived by

Hildebrand[22,35], *Sasaki*[36] and *Santos*-Lozano[28] will also be used to determine physical activity, sedentary time, and PAEE.

SenseWear Armband Mini Monitor (SWAM)

Participants were instructed to wear the SWAM for the entire 14-day period that the GT3X+ was also worn, with the exception of during water activities. Data were analyzed using the manufacturer provided software (SenseWear Professional 8.0, BodyMedia, Inc). The software uses data from the monitor's sensors (heat flux, galvanic skin response, skin temperature, and near body ambient temperature) and individual information (age, sex, height, weight, smoking, and handedness) to give estimates of EE for each minute of wear time. EE estimates for each minute are then converted to METs which are then used to classify activity intensity. METs for sedentary, light, moderate, and vigorous activity are 1-1.5, 1.6-2.9, 3-5.9, and $\geq$ 6 METs respectively.

Data Analysis

Discrepancy Analysis

Means and Standard Deviations will be calculated for PAEE and physical activity and sedentary time derived from DLW, GT3X+ and SWAM. Linear regression will be used to determine the relationship between DLW and GT3X+ estimates of PAEE. Interclass correlations (ICCs) will be used to assess agreement between the PAEE measures. Bland-Altman plots will be used to determine mean bias, trends, and the degree of agreement within the 95% confidence intervals of PAEE estimates between GT3X+ and DLW-determined PAEE and PAEE estimates between GT3X+ and SWAM. All statistical analyses will be performed using SAS software (SAS Institute, Cary, NC).

The cut points that produce the most accurate estimates will be used for the epoch-by-epoch (EBE) analysis.

Epoch-by-Epoch (EBE) Analysis

Epoch-by-epoch data will be obtained from both monitors. Readings from both devices will be confined to the same time period. The SWAM was removed during water activities while the GT3X+ was not. Therefore, periods of time where the SWAM was removed will be excluded from the EBE analysis.

Error matrices will be computed to evaluate physical activity intensity detection. This will be done by creating a column for each device and matching the 60 sec epochs by the time they were recorded. Each epoch will be given a code to identify its activity intensity. Sedentary activity will be coded as 0, light activity will be coded as 1, moderate activity will be coded as 2, and vigorous activity will be coded as 3. For each epoch, the GT3X+ will be evaluated on whether or not it agreed with the SWAM on activity intensity. EBE metrics will be computed to evaluate the sensitivity, specificity, and positive predictive value of the device. Sensitivity will refer to the ability of the device to correctly classify activity epochs. Specificity will refer to the ability of the device to correctly classify sedentary epochs. Positive predictive value will refer to the probability of a given epoch to be in a given activity intensity based on the device classification.

Strengths and Limitations

The use of the DLW as the criterion method is a strength of this study since it is considered the gold standard in techniques measuring EE. However, it is important to note that the method still has a 5-10% measurement error.[7] Other strengths include objectively determined PA and sedentary time, long wear time of the activity monitors each day, the number of days the women wore the activity monitors, and matching monitor wear time and DLW measurement period.[27]

Despite many strengths, there are still limitations to our study, one being our participant sample. The participants enrolled in the study were non-obese inactive older women and it is well known that validity of accelerometry algorithm may be affected by age and activity level. Therefore, the results of this study cannot be generalized to populations outside of this study sample. Also, RMR was only measured once and was used as a representation of the individuals average RMR.

LITERATURE REVIEW

This section will review the history and details of accelerometer use, EE and how it is measured, the function and validity of the SWAM in measuring EE, and the function and validity of the GT3X+ in measuring EE.

History of Accelerometers

Accelerometers can be uni-axial, bi-axial, and tri-axial which refers to the number of planes in which the device is able to measure acceleration. A tri-axial accelerometer can sample acceleration in three perpendicular planes (X, Y, and Z axes). Tri-axial and multisensor accelerometers have shown the best validity.[37] Activity counts are the raw outputs produced by accelerometers and the number of counts per minute is used to determine sedentary time and physical activity intensity.[38] Thresholds of activity counts are used to determine sedentary time or activity intensity.

The first attempt at accelerometer use was as early as the 1950s.[39] However, due to the bulky nature of the device, it was not deemed a viable option.[10] Accelerometry reappeared on the scene in the 1970s when Morris proposed that it had many advantages over the commonly used methods of the time.[40] Later in the 1980s, Montoye et al discovered that accelerometers were likely able to objectively assess physical activity intensity.[38,41] Currently, accelerometers are widely used as a valid method of estimating EE as several studies have validated their use against the DLW.[10,11,30,37,38,42]

A common disadvantage of accelerometers is the underestimation of PAEE at slow walking speeds. A systematic review of 134 validation studies found that accelerometry underestimated EE during slow walking speeds in 69% of the studies.[37] This poses a problem when measuring EE in the elderly or populations with chronic diseases or disabilities since they tend to move less and at slower speeds.

Although they have their disadvantages; accelerometers hold many benefits. While the DLW can only give total EE over a specified time period, accelerometers are able to give PAEE, along with duration, frequency, and intensity of activity. Furthermore, it is practical for use outside of a lab setting and does not require anything from a participant other than wearing it. Accelerometers are small, unobtrusive, and cost much less when compared to the DLW or IC.

Accelerometers can be worn at many different places on the body such as the arm, leg, wrist, ankle, or hip. The most common accelerometer placement is the hip because it is close to the center of mass.[11,42] However, this is not always the most comfortable placement and there are several disadvantages to using this placement. Arm movements created by activities like stair climbing, walking, swimming, carrying objects and pushing and pulling objects are many times undetected by the accelerometer when worn on the hip. This results in an underestimation of PAEE.[11,38,43,44] Furthermore, the hip placement may not be comfortable for daily activities, such as sleeping. There is evidence to suggest that wrist-worn accelerometers may improve participant compliance. A substantial improvement in compliance was seen in the 2011-2014 NHANES survey when the wrist placement was used as opposed to the 2003-2005 NHANES survey when the hip placement was used.[20] Also, previous research has suggested that unobtrusive devices that integrate measurement into devices already accepted by a large number of people are effective in improving patient compliance.[16] Therefore, the wrist placement would likely be more easily accepted by participants since it is most closely related to a device many wear already, thus creating less participant burden.

In summary, accelerometers have become a common, objective measure of estimating EE and physical activity intensity. Accelerometers are able to give day to day estimates of free-living EE, which make it a practical choice. Furthermore, they tend to be much more accurate than self-report measures without being astronomical in cost. There are currently many different accelerometers on the market, all of them having different levels of validity. The GT3X+ is a popular accelerometer used in research that can be worn on the hip or the wrist. Most of the work aiming to validate this monitor has been done using the hip placement. However, the device shows promise for being able to produce accurate estimates of EE and physical activity intensity when worn on the wrist. Due to the comfortability of the wrist placement and its potential to increase wear compliance, it is worthwhile to explore the validity of the GT3X+ when worn on the wrist.

Measurement of Energy Expenditure

EE is a measure of the amount of energy an individual uses in the form of calories. TDEE refers to how much energy is expended in an entire day while PAEE refers to the amount of energy expended or used during physical activity.[33] EE plays an important role in maintaining body weight. Therefore, being able to accurately measure EE is beneficial in helping individuals maintain a health energy balance.

The gold standard for measuring TDEE is by using the DLW. This method involves the consumption of a known dose of doubly labeled water ($^2H_2\ ^{18}O$) and the collection of periodic urine samples in order to determine the rate of $^2H_2$ and ^{18}O elimination. $^2H_2$ washes out of the body as water and ^{18}O washes out of the body as water and CO_2. The difference between the elimination rate of $^2H_2$ and ^{18}O provides a value of CO_2 production which can then be used to estimate EE. The unobtrusive nature of this method makes it a practical choice for field studies since it does not require the constant measurement of expired CO_2, but periodic urine samples instead, allowing participants to go about their daily activities.[7]

Another method of measuring EE is IC. IC is also often used as a criterion method when aiming to validate other methods of measuring EE. IC involves using gas exchange measurements, O_2 uptake and CO_2 release, to estimate EE. Although IC is a valid method for estimating EE, it is not practical outside of a lab setting due to the fact that it requires a metabolic cart. In order to collect respiration measures, an individual must wear a mask with a tube connecting them to a metabolic cart that measures the volume of CO_2 production and O_2 production through gas analysis.[45,46] RMR is a method of measuring an individual’s resting EE and the procedures used are similar to that of IC. The main difference is that participants are resting underneath a ventilated hood rather than wearing a mask that allows them to participate in physical activity. RMR is needed to determine

PAEE. PAEE can be calculated from TDEE with the following equation (TDEE*0.9 - RMR).[25,26]

Function and Validity of the SenseWear Armband Mini Monitor (SWAM)

The SWAM is a multisensor monitor that is worn on the upper arm, over the triceps. This device combines accelerometry with temperature sensors, skin galvanic response sensors and heat flux sensors. These measures are used in a proprietary algorithm along with demographic information in order to estimate EE, sedentary time, and time spent in MVPA.

Although the SWAM is not produced anymore, it has been validated in several studies,[47-49] and therefore is useful when determining the accuracy of the other device for estimating EE. The first study to investigate the validity of the SWAM included 30 healthy participants (15 men and 15 women), whose ages ranged from 24 to 60 years. According to BMI, 27% of the participants were classified as overweight and 10% were classified as obese. The participants wore the SWAM for 14 consecutive days, including during sleep. The DLW was used as the criterion measure of EE. According to Paired- t-tests, no significant differences were found in TDEE estimates between the SWAM and the DLW ($p = 0.69$). During regression analysis, significant agreements in TDEE estimates between the SWAM and DLW were seen ($R^2=0.71$, $P<0.001$). ICC for the SWAM and DLW was 0.85 (95% CI=0.92-0.76), indicating that only 15% of the variation in TDEE measures was attributed to the variation between the SWAM and DLW methods. Plots of the residual values showed an overestimation of TDEE at low levels of EE and a significant underestimation of TDEE at higher levels of EE. A secondary analysis of this study looked at agreement of PAEE estimates from the SWAM compared to the DLW. It was found that the SWAM significantly underestimated PAEE when compared to the DLW ($p=0.03$). Regression analysis revealed a moderate agreement between SWAM and DLW PAEE ($R^2 = 0.48$, $p<0.001$). ICC of PAEE estimates between the SWAM and DLW was 0.63, indicating that 37% of the variation in the measurements was attributed to the variation between SWAM and DLW methods. The authors concluded that the SWAM was able to accurately estimate TDEE under free-living conditions but did not perform as well when it came to estimating PAEE. However, this could be due to the fact that they used an estimation equation to calculate RMR and not IC.[47]

Calabró et al investigated the validity of six different commercially available activity monitors, one of them being the SWAM, in a population of 40 healthy men and women. The participants were between 18 and 53 years old with BMI's ranging from 17.8 to 29.0 A portable metabolic analyzer was used as the criterion measure and the subjects performed 60 minutes of structured cardiovascular activities and 60 minutes of unstructured light intensity activity. A strong correlation was seen between the metabolic analyzer and the SWAM ($r = 0.89$). The Bland-Altman plots revealed no systematic bias and the narrowest 95% limits of agreement for the SWAM (difference =1.6 METs) compared to the other monitors. In the end, the SWAM provided no significant differences compared to the criterion measure.[48]

A study aiming to validate the SWAM's ability to estimate EE in pregnant women found that overall, estimates from the SWAM correlated well with IC. This study enrolled 30 healthy pregnant women and had them complete a series of activities of daily living while EE was estimated by SWAM and IC concurrently. The activities performed included typing, laundry, sweeping, and treadmill walking at 2, 2.5, and 3mph and 3mph with a 3% incline. The authors also processed the data using two different versions of the data processing software to see how the estimates varied between algorithms. For the purpose of this review, only the estimates from the newest version of the processing software will be reported on. Mixed model analyses revealed a significant main effect by method (F=158.99, P<0.0001). Post hoc tests revealed no significant differences between IC and SWAM for typing, sweeping, and inclined walking (P<0.0001). Mean individual correlation coefficient for the entire protocol was 0.87. Bland-Altman plots showed tight cluster of data points around the mean and a minimal mean bias of -0.57kcal/min. The authors conclude that the SWAM showed strong overall agreement with IC. However, for all activities, except incline walking, the SWAM significantly overestimated EE. The authors speculate that this overestimation may be due to the change in body composition associated with pregnancy (greater proportion of inactive tissue).[49]

There are several advantages to using the SWAM. The SWAM provides direct estimates of wear time and direct estimates of EE. The direct estimates of EE are highly beneficial because of the simplicity it provides over the numerous estimation equations for different populations that are present in the literature.[47] Unfortunately, the SWAM is no longer being produced, thus increasing the need for more valid activity monitors that unobtrusive, comfortable, minimize participant burden.

Function and Validity of the Actigraph accelerometer GT3X+

The GT3X+ is a triaxial accelerometer that objectively measures free-living activity. The GT3X+ contains both an acceleration sensor and an ambient light sensor. Acceleration data sampling rates range from 30 to 100 Hz and are stored as raw activity counts. Activity counts per minute are then compared to activity count thresholds to determine activity intensity. Counts per minute thresholds are usually determined by the device manufacturer but may be manipulated during processing to fit the needs of the sample demographic. Using ActiLife's proprietary software, EE is estimated from the activity intensity data. The user manual recommends the device be worn on the hip, close to the body's center-of mass, when collecting daytime EE, and anywhere on the body (wrist, hip, arm, or ankle) when collecting sleep data.[12] Wrist-worn EE measures have not been validated, however there is a possibility that they may produce reliable measures. Wearing it on the wrist may decrease participant burden, while allowing the researcher to collect data on physical activity, EE, and sleep.

Validity of the Hip-worn GT3X+

The majority of studies aiming to validate the GT3X+ for use in estimating PAEE have used the hip placement. A study by Gastin et al had 26 participants complete a 90 min session that consisted of walking, jogging, running, and a sport-simulated circuit. Exercise bouts were 5 min long and were separated by 10 min bouts of rest. PAEE was measured by GT3X+ and IC concurrently. The investigators found that the GT3X+ significantly underestimated PAEE by 374.5kJ during the 90 min bout of physical activity compared to PAEE estimates derived from IC ($P < 0.05$). Furthermore, when compared to IC, the GT3X+ was found to significantly overestimate PAEE during walking and jogging (25.3%, 16.8%, percent difference, respectively, $p< 0.01$) while significantly underestimating PAEE during running and circuit intervals (-14.0%, -59.1%, percent difference, respectively, $P< 0.01$). The authors concluded that the GT3X+

failed to provide accurate estimates of PAEE across a range of exercise types and intensities compared to IC.[15]

Ceaser examined the validity of the GT3X+'s ability to measure PAEE when placed on the hip compared to IC. A sample of 21 healthy, college-aged-adults volunteered and participated in a total of 17 activities while wearing the monitor and a portable metabolic analyzer. In order to determine significant difference from the criterion method paired sample t-tests with Bonferroni adjustments were used ($p<0.05$). The test showed that the GT3X+ significantly overestimated PAEE during nearly all walking activities such as self-paced walking, walking with an umbrella and walking with a backpack, and underestimated PAEE during activities with arm movements such as vacuuming, sweeping, dishwashing, mowing, raking, racquetball, and basketball. Ceaser concluded that the GT3X+ overestimated PAEE during walking and underestimated PAEE during activities with arm movements.[14]

In contrast to the aforementioned study, a study looking to validate the GT3X+ for PAEE when worn on the hip found much more promising results. This study included a total of 52 participants, ages 18-65 years. PAEE was estimated while participants completed 20 min of sedentary activity, 25 min of aerobic exercise, and 25 min of resistance exercise. The participants wore a total of seven activity monitors, one of them being the GT3X+. The GT3X+ was worn on the hip and PAEE estimates were compared to IC. Mean bias, equivalence testing, and correlations showed that EE estimates from the GT3X+ were equivalent to those from IC (±10% equivalence zone) with a mean bias underestimation of EE by 11.9 kcal and a correlation of 0.73.[13]

The validity of the hip worn GT3X+ is acceptable throughout a range of activity modalities and intensities. However, the hip placement presents challenges with wear compliance and under detection of activities with substantial arm movement. Due to the many disadvantages of the hip placement, it is worthwhile to look into the validity of the GT3X+ when worn on the wrist. The familiar and unobtrusive nature of the wrist placement alone should prompt further validation of wrist-worn accelerometers.

Validity of the Wrist-worn GT3X+

Far fewer studies have looked at the validity of the GT3X+ compared to a criterion measure when worn on the wrist and even fewer studies have compared the validity of the hip and wrist placements in estimating PAEE. Only one study was found that used the wrist placement, a criterion measure, and examined both placements. McMinn et al aimed to determine the validity of GT3X+'s ability to estimate PAEE under controlled walking conditions and examined the agreement between the hip and wrist placements. A total of 19 participants, aged 19-53 years old, completed three walking trials: a slow-walking trial, a medium-walking trial, and a fast-walking trial. The study compared PAEE estimates from the GT3X+ to indirect calorimetry (IC) and found that PAEE estimates from the GT3X+ highly correlated with IC (hip: $r = 0.82$, wrist: $r = 0.72$). However, Bland-Altman plots revealed that the GT3X+ (hip and wrist) significantly underestimated PAEE during slow walking (mean difference of 0.77 and 1.22 for hip and wrist respectively) and significantly overestimated PAEE during fast walking (mean difference of -1.9 and -0.96 for hip and wrist respectively). No differences were seen between the hip and wrist placements during the medium walking trial. McMinn ultimately concluded that the GT3X+ shows high correlation with IC measured

PAEE but poor agreement during slow and fast walking trials, and when worn on the wrist, the GT3X+ tended to underestimate EE at rates above 4 kcal·min^{-1}. [21]

Hildebrand et al compared the raw accelerometer outputs of the GT3X+ and the GENEActiv accelerometer from both the hip and wrist placement in 30 children and 30 adults during a range of activity intensities. The activities performed ranged from lying down to running and a total of four monitors were worn (a GT3X+ on the hip and wrist and a GENEActiv on the hip and the wrist). For the purpose of developing regressing equations for estimating EE, VO_2 was measured by IC. ICCs using a two-way mixed model ANOVA were used to assess the agreement between the two placements. Linear regression analyses were also performed to determine the relationship between accelerometer output and VO_2 from the two different placements. Increases in VO_2 tended to correlate with an increase in output from both placements with the exception of a low output compared to VO_2 during a step activity in the protocol. A factorial ANOVA showed a significant effect of activity ($F_{2.1,47.9} = 355.2$, $F_{1.3,35.5} = 1031.7$, $P < 0.0001$) and placement ($F_{1.0,23.0} = 31.7$, $F_{1.0,27.0} = 83.3$, $P < 0.0001$) in both children and adults with the wrist placement of the monitors producing significantly higher outputs than the hip placement ($p<0.001$). ICC between different placements of the GT3X+ was 0.905 with a CI of 0.903-0.907 in adults and 0.917 with a CI of 0.916-0.919 in children. The wrist placement did not perform as well as the hip placement, many times producing significantly higher output than the hip worn monitors. However, the authors mention that taking into account the less obtrusive nature of the wrist placement, the ability to improve wear compliance makes the wrist placement a viable option.[22]

There is evidence to suggest that the wrist placement of accelerometers may be useful in predicting PAEE in some special populations. Nightingale et al examined the validity of the GT3X+ and the GENEActiv accelerometer at both the wrist and upper arm (UA) locations in 17 manual wheelchair users. The participants wore a total of 4 accelerometers, one at each location, while performing a total of 10 activities. PAEE was concurrently measured with IC. Linear regression analysis revealed higher correlations for the wrist placement of both monitors (GT3X+: r = 0.82 GENEActiv; r = 0.88) when compared to the UA placement (GT3X+: r = 0.68, GENEActiv; r = 0.87). In conclusion, the wrist placement seems to be the most appropriate placement of the GT3X+ in this population.[50]

A previous ActiGraph model has shown similar results in wheelchair users. A study done in 20 full time wheelchair users with spinal cord injuries aimed to validate the ActiGraph model GT3X in this population while also determining the best placement. The participants wore the GT3X on 4 different placements including the chest, hip, and both wrists. Oxygen consumption (VO_2) was measured via a portable metabolic analyzer and the participants completed a total of 10 housework activities while wearing the accelerometers and the metabolic analyzer. Multiple linear regression models were used to examine the validity of the accelerometer outputs compared to VO_2. The non-dominant wrist placement turned out to be the most accurate placement with an r-value of 0.86 and root mean square error of 2.23 ml kg^{-1} min^{-1}.[51] Although wheelchair users present very different activity patterns than a population of healthy individuals, the validity of the wrist placement in wheelchair users indicates that this placement may be useful in other populations as well.

Although only one study aiming to validate the wrist placement for EE estimates was found and only a few were found that compare EE estimates between the two placements, there are studies that have looked at the ability of the two placements to accurately classify physical activity and sedentary time. This is beneficial because a monitor's ability to classify physical activity and sedentary time can affect its ability to produce accurate EE estimates. A study by Ellis et al aimed to compare accuracy of behavior classifications made between the hip and wrist placement of the GT3X+.[17] For seven days, participants wore two accelerometers (one on the hip and one on the wrist) and a camera that captured images every 20 seconds in order to attain information about true participant behavior. Chi-square tests ($p < 0.01$) were used to determine significant difference from true behavior. Both placements significantly overestimated time standing but estimated time sitting and riding in a vehicle were not significantly different from true behavior. Bland-Altman plots for minutes walking show no bias with increasing time for both the hip and wrist placement, indicating good agreement. The authors concluded that both placements provided accurate estimates of sedentary and walking minutes.

ActiGraph accelerometers have been shown to produce estimates of PAEE that agree with previous generations of their accelerometers.[52,53] Therefore, the validity of the previous generations can provide insight into the potential validity of the GT3X+. A study done in 40 Swedish preschool children aimed to determine the validity of the Actigraph wGT3X-BT to predict PAEE when worn on the wrist. The DLW was performed over 14 days in order to determine TDEE. PAEE was calculated as [(0.9*TDEE)-predicted RMR]. PAEE derived from the DLW was compared to PAEE estimates from the wGT3X-BT. Wear compliance was extremely high with 95% of the children wearing the device for at least 6 days and 85% of them wearing it for the entire 7-day period. Regression analyses were performed to examine the variation in PAEE explained by the wGT3X-BT by itself and in conjunction with age, gender, weight, fat mass, and fat free mass. When fat and fat free mass were incorporated into PAEE estimation from the wGT3X-BT, 62% of the variation in PAEE was explained. Bland-Altman plots showed wide limits of agreement, however, the mean bias was only 0.2% and no strong trends in the data were seen. Based on these results, the authors reason that the wrist placement has potential to provide valuable information in research due to the high wear compliance associated with the placement.[54]

Summary

In conclusion, the wrist placement of accelerometers shows promise for improving wear compliance in research. However, more work needs to be done to validate the GT3X+ for estimating PAEE when worn on the wrist in healthy populations across a range of activity intensities. Furthermore, there is a lack of studies aiming to validate the GT3X+ in a population of non-obese older women. Therefore, this study will be able to fill that gap in the literature. Based on the validity of the device when worn on the hip and its ability to accurately classify physical activity and sedentary behavior when worn on the wrist,[17] the GT3X+ should be able to provide accurate EE estimates when worn on the wrist. Furthermore, the favorable performance of the wrist placement in wheelchair users should prompt investigation into whether the same level of validity holds in other populations. This study will be the first, to our knowledge, to examine the validity of the GT3X+ to accurately estimate PAEE when worn on the wrist in a population of non-obese, older women. In this thesis, PAEE estimates from the wrist-worn GT3X+ will be compared to those from the DLW and SWAM in order to investigate its validity in this population.

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