Validity of the SenseWear armband step count measure during controlled and free-living conditions

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Abstract

Background/Objective: Advances in technology continue to provide numerous options for physical activity assessment. These advances necessitate evaluation of the validity of newly developed activity monitors being used in clinical and research settings. The purpose of this study was to validate the SenseWear Pro3 Armband (SWA) step counts during treadmill walking and free-living conditions.

Methods: Study 1 observed 39 individuals (17 males, 22 females) wearing an SWA and a Yamax Digiwalker SW-701 pedometer (DIGI) during treadmill walking, utilizing manually counted steps as the criterion. Study 2 compared free-living step count data from 35 participants (17 males, 18 females) wearing the SWA and DIGI (comparison) for 3 consecutive days.

Results: During Study 1, the SWA underestimated steps by 16.0%, 10.7%, 5.6%, 6.1%, and 6.5% at speeds of 54 m/min, 67 m/min, 80 m/min, 94 m/min, and 107 m/min, respectively, compared to manually counted steps. During Study 2, the intraclass correlation (ICC) coefficient of mean steps/d between the SWA and DIGI was strong ($r = 0.98, p < 0.001$). Unlike Study 1, the SWA overestimated step counts during the 3-day wear period by an average of 1028 steps/d (or +11.3%) compared to the DIGI. When analyzed individually, the SWA consistently overestimated step counts for each day ($p < 0.05$).

Conclusion: The SWA underestimates steps during treadmill walking and appears to overestimate steps during free-living compared to the DIGI pedometer. Caution is warranted when using the SWA to count steps. Modifications are needed to enhance step counting accuracy.

Keywords: Accelerometry; Armband; Assessment; Evaluation; Physical activity

Introduction

Accurately and reliably quantifying physical activity is a fundamental objective for researchers and clinicians observing habitual physical activity. Ambulatory activities, such as walking, jogging, and running, are by far the most common forms of physical activity performed by adults. In addition, walking is the mode most commonly recommended by clinicians in regard to improving health, and by researchers implementing health-related interventions (i.e., cardiovascular disease, diabetes, physical inactivity, etc.). The use of walking in these settings calls for activity monitors that accurately estimate step counts.

Pedometers are inexpensive, unobtrusive monitors that provide instantaneous stepping information with interfaces and metrics that are easily interpretable. Clinicians and researchers commonly recommend that individuals utilize pedometers to aid in achieving specific daily step count goals, in order to improve health in clinical and intervention settings. Further, some clinicians prescribe patients to accumulate steps in certain activity intensity zones that are associated with improved health (i.e., light, moderate, vigorous, and vigorous+). Most pedometers, however, are incapable of categorizing steps into activity intensity zones. Considering this, alternative monitors are required to assess the intensity of steps taken in addition to accurately quantifying step counts.

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With advances in technology, physical activity monitors are becoming more complex and are capable of providing higher level metrics, such as minutes of moderate to vigorous physical activity (MVPA) and energy expenditure (EE). Accelerometers provide a feasible option for monitoring activity in terms of cost and usability in practical settings.\textsuperscript{1,3} Although measures like MVPA and EE are beneficial, such metrics are less interpretable to the layperson than steps.\textsuperscript{6,7} Monitors that provide multiple measures of physical activity, while including accurate stepping information, might assist the layperson in developing an understanding of the relationship between their stepping activity and MVPA/EE, which could lead to more successful interventions.\textsuperscript{12}

The SenseWear Pro3 Armband (SWA) is a pattern recognition monitor that incorporates accelerometry to count steps. Additionally, the SWA uses heat flux, skin temperature, galvanic skin response, and anthropometrics to estimate total (resting and activity) EE and intensity of activities. The SWA can be used in conjunction with a wrist-watch-like device that offers immediate feedback on daily steps, EE, and MVPA. Users can log SWA data daily and examine their daily physical activity with the variety of metrics offered. This allows wearers the option to incorporate their steps-to-EE relationship into their energy balance estimations, which could result in more successful diet planning and activity interventions. For example, Shuger et al\textsuperscript{13} used the SWA in a 9-month weight loss intervention that compared three groups [an SWA alone, a group weight loss (GWL) program alone, or SWA + GWL]. The groups that incorporated the SWA (which included daily uploading of SWA data) lost significantly more weight than the GWL and control groups. This finding shows that the SWA has the potential to aid in behavior modification in interventions focused on weight loss.

Numerous articles have identified that pedometers/step counting can assist individuals in modifying behaviors.\textsuperscript{12,14--16} Although speculative, it may be that the SWA can be used in this fashion. Considering the SWA watch can be worn in conjunction with the SWA and display up-to-the-minute daily step counts (along with other metrics), it too may prove to be an effective intervention tool. In addition, the ability to log SWA activity data may facilitate the potential for wearers to learn how metrics, such as EE and MVPA, relate to their stepping habits, which are commonly more interpretable to the layperson, thus, learning to utilize the SWA to its full potential as an activity monitor and possess a better understanding of how their stepping activity impacts their health and energy balance. To our knowledge, no study has reported on the validity of the SWA to assess step counts in a population of young adults in laboratory-based and free-living conditions. The aim of this study was to determine the accuracy of the SWA to assess steps in free-living and controlled conditions.

**Methods**

**Participants**

A convenience sample of young adults aged 19.0–28.4 years were recruited from kinesiology courses at a Midwestern university to participate in Study 1 (treadmill walking; \(n = 39\); 17 males, 22 females) and a subset of these agreed to also participate in Study 2 (free-living) (\(n = 35\); 17 males, 18 females). Individuals with walking impairments or utilizing walking aids were excluded from the study. Height and weight were recorded via a stadiometer (Detecto ProDoc PD300, Webb City, MO, USA) in light clothing without shoes. Height was recorded to the nearest cm and weight was recorded to the nearest 0.1 kg. The procedures were reviewed and approved by the Institutional Review Board at Illinois State University, Normal, IL, USA. Each participant completed a medical history questionnaire and gave informed consent prior to participating in the study.

**Equipment**

For both Study 1 and Study 2, participants wore a Yamax Digiwalker SW-701 pedometer (Digi; YAMAX International, Tokyo, Japan) on the right hip along with an SWA (BodyMedia Inc., Pittsburgh, PA, USA) on the back of the right triceps. The SWA utilizes a biaxial accelerometer to register the movement of the upper arm to estimate motion and steps taken and reports them on a minute-by-minute basis (step counts sampled once/ min). All monitors were worn in accordance with the manufacturer’s recommendations and underwent a 20-step test for calibration. A researcher hand tallied steps with a manual counter during Study 1 to count steps, providing a criterion measurement, whereas during Study 2, the Digi was used as the comparative device.\textsuperscript{17--20} Schneider et al\textsuperscript{20} considered the Yamax Digiwalker SW-200 against 13 pedometers in free-living conditions (including a 2nd Yamax Digiwalker SW-200 and a Digi). The Yamax Digiwalker SW-200 was used as the comparative device based on its performance in previous validation studies, specifically at self-selected paces. Participants wore the criterion pedometer along with one other pedometer for a 24-hour period, switching pedometers in a randomized order daily and tracking step counts for each pedometer worn daily. It was concluded that five of the 13 pedometers should be considered for use in free-living settings, including both the Yamax Digiwalker SW-200 and the Digi.

**Study 1 protocol**

The purpose of Study 1 was to validate step counts of the SWA compared to the Digi and a criterion measure, manually counted steps. The agreement of the Digi and SWA step counts at the various speeds used during treadmill walking was also observed. After measuring height and weight, participants were fit with a Digi and an SWA. Next, they walked on a treadmill for five stages at speeds of 54 m/min, 67 m/min, 80 m/min, 94 m/min, and 107 m/min at 0% grade (which is equivalent to 3.2 km/h, 4.0 km/h, 4.8 km/h, 5.6 km/h, and 6.4 km/h, respectively). Each stage was 3 minutes in duration, with a 2-minute break between each stage, during which participants straddled the treadmill and stood motionless while researchers recorded step counts from the counter and the Digi. When participants stepped onto the treadmill belt, they...
were asked to let go of the treadmill upon beginning their stepping motion, so that their arms were allowed to swing normally. At the conclusion of the final stage, data from the SWA was downloaded and step counts for each stage were recorded.

**Study 2 protocol**

The purpose of Study 2 was to observe the agreement of step counts between the SWA and the DIGI in free-living conditions. Participants wore the SWA and DIGI for 3 full days. They were instructed to wear the devices at all times, excluding during sleep and water-based activities (i.e., showering or swimming). Individuals were instructed to remove both monitors if either one was removed for any reason. Due to the inability of the DIGI to distinguish between days, participants received a step count log to write down how many steps the DIGI recorded each night after removing the devices before going to bed. They also reset the DIGI each morning upon replacing the devices for the day. Participants kept a monitor log sheet to record when monitors were removed and replaced for verification purposes. At the end of the 3-day period, participants returned the devices and DIGI step-log for analysis. To ensure compliance, participants were given a detailed verbal explanation of study requirements, encouraged to contact study investigators with any concerns, and were given a handout providing bullet-points recapping the study requirements. Overall, only two individuals were excluded from the analysis due to problems with the batteries in the SWA.

**Statistical analysis**

In both studies, descriptive statistics were calculated for participant characteristics as mean (standard deviation). In Study 1, intraclass correlations (ICCs) were used to determine the consistency in associations between steps recorded by the manually counted steps (criterion) and DIGI, manually counted steps and SWA, and the DIGI and SWA at each of the five treadmill speeds. A 3 × 5 repeated measures analysis of variance (ANOVA) was used to identify potential differences between the monitors and manually counted steps across the different treadmill speeds. Post hoc least significant difference tests utilizing the Bonferroni technique were used to identify the speeds where differences between monitors occurred. Standard error of measurement (SEM) was computed to provide information about the variation in steps between the criterion and the DIGI and SWA during each stage. Agreement between the SWA and manually counted steps was also assessed using Bland–Altman plots at two treadmill speeds.

In Study 2, ICCs were used to characterize the consistency in the associations between steps recorded by the SWA and DIGI for the 3-day average of free-living steps. A paired-samples t test determined if a difference existed in steps recorded between the monitors. SEM was calculated to provide a potential range for step counts. Additionally, agreement between the average daily step counts of the SWA and DIGI steps was assessed using Bland–Altman plots. For both studies \( \alpha < 0.05 \) was used to determine statistical significance. All analyses were performed using IBM SPSS Statistics version 20 (IBM Corp., Armonk, NY, USA).

**Results**

**Study 1**

Descriptive statistics for both studies are provided in Table 1. Both monitors were more accurate at higher speeds than lower speeds (54 m/min and 67 m/min). Fig. 1 shows the effect speed has on the accuracy of each monitor at each speed during treadmill walking. Bland–Altman plots for the number of steps depict an average underestimation of 32.5 steps for the SWA compared to manually counted steps during treadmill walking at 67 m/min (Fig. 2) and an underestimation of 21.4 steps at 94 m/min (Fig. 3). The ICCs between manually counted steps and each monitor and between the DIGI and SWA are reported in Table 2. In general, the ICCs between

![Fig. 1. Effect of speed on monitor accuracy (% of manual count) during treadmill walking.](image-url)
manually counted steps and each device and between the DIGI and SWA strengthened as speed increased. The results of the ANOVA (Table 3) indicated that the SWA significantly underestimated steps taken at each speed compared to manually counted steps (all $p < 0.05$). The DIGI also significantly underestimated steps compared to manual count at 54 m/min and 67 m/min (both $p < 0.05$), but was similar at the higher speeds. Comparing the steps recorded by the DIGI and SWA, significant differences existed at speeds of 94 m/min and 107 m/min (both $p < 0.05$), but the monitors were comparable at the slower speeds. The SEM was calculated to provide a measure of variability in step counting error by the monitors at

<table>
<thead>
<tr>
<th>Speed (in m/min)</th>
<th>Manual count and DIGI</th>
<th>Manual count and SWA</th>
<th>DIGI and SWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>0.43</td>
<td>0.39</td>
<td>0.63*</td>
</tr>
<tr>
<td>67</td>
<td>0.60*</td>
<td>0.41</td>
<td>0.66*</td>
</tr>
<tr>
<td>80</td>
<td>0.80*</td>
<td>0.78*</td>
<td>0.68*</td>
</tr>
<tr>
<td>94</td>
<td>0.91*</td>
<td>0.81*</td>
<td>0.74*</td>
</tr>
<tr>
<td>107</td>
<td>0.99*</td>
<td>0.80*</td>
<td>0.80*</td>
</tr>
</tbody>
</table>

* Indicates intraclass correlation was statistically significant ($p < 0.05$).
each speed and these results are reported in Table 3. Mean differences and 95% limits of agreement (LoA) results from Bland—Altman plots for DIGI and SWA compared to manually counted steps are presented in Table 4.

**Study 2**

During free-living, the ICC between mean steps/d between the SWA and DIGI was strong ($r = 0.98 \ p < 0.001$). The results from the paired-samples $t$ test and the SEM between the SWA and DIGI are reported in Table 5. In contrast to the treadmill testing, the SWA significantly overestimated steps taken compared to the DIGI by an average of 1023 steps/day ($p < 0.001$). When analyzing each day individually, this overestimation was consistent for each of the 3 days measured (all $p < 0.05$). A Bland—Altman plot observing the agreement between mean daily step counts between the DIGI and SWA showed the mean bias between the monitors was 1023 steps/day and the 95% LoA were wide ranging from $-1501$ to 3548 steps/d (Fig. 4).

**Discussion**

To our knowledge this is the first study to report on the SWA step count metrics during free-living conditions in a population of young adults. Additionally, we investigated the accuracy of the SWA to count steps during treadmill walking. In both instances, the steps recorded by the SWA were significantly different than the comparative measure employed. Interestingly, we found that the SWA underestimated steps during treadmill walking but overestimated steps during free-living.

During treadmill walking, the SWA underestimated steps at all speeds compared to manually counted steps and was least accurate at the slowest speeds (54 m/min and 67 m/min). However, the SWA was only significantly different from the DIGI at speeds of 94 m/min and 107 m/min. Arvidsson et al. investigated the accuracy of the SWA during treadmill walking in normal and high BMI African American children. They also reported that the SWA significantly underestimated steps at slower treadmill speeds, and became more accurate as speed increased. Dwyer et al. evaluated the accuracy of the SWA to count steps during treadmill walking in a blended group of individuals with and without cystic fibrosis. Similar to our findings, they also reported that the SWA significantly underestimated steps at slower treadmill speeds, and became more accurate as speed increased.

### Table 3

Comparison of step count by Yamax Digiwalker SW-701 pedometer (DIGI) and SenseWear Pro3 Armband (SWA) to manually counted steps during treadmill walking.

<table>
<thead>
<tr>
<th>Walking speed (m/min)</th>
<th>Manual count</th>
<th>DIGI</th>
<th>SWA</th>
<th>Difference from manual count</th>
<th>Standard error of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 steps</td>
<td>11,332 (6855)</td>
<td>12,202* (6551)</td>
<td>9438 (5305)</td>
<td>Average daily steps</td>
<td>Day 1 steps</td>
</tr>
<tr>
<td>Day 2 steps</td>
<td>11,477 (6870)</td>
<td>9438 (5305)</td>
<td>10,596* (5424)</td>
<td>Average daily steps</td>
<td>Day 2 steps</td>
</tr>
<tr>
<td>Day 3 steps</td>
<td>11,477 (6870)</td>
<td>9438 (5305)</td>
<td>10,596* (5424)</td>
<td>Average daily steps</td>
<td>Day 3 steps</td>
</tr>
<tr>
<td>Average daily steps</td>
<td>10,159 (4227)</td>
<td>11,182* (4439)</td>
<td>11,182* (4439)</td>
<td>Average daily steps</td>
<td>Day 3 steps</td>
</tr>
</tbody>
</table>

Data are presented as mean (SD). * Indicates SWA significantly different from DIGI ($p < 0.05$).

### Table 4

Bland—Altman results for SenseWear Pro3 Armband (SWA) and Yamax Digiwalker SW-701 pedometer (DIGI) for all treadmill speeds.

<table>
<thead>
<tr>
<th>Walking speed (m/min)</th>
<th>Agreement (%)</th>
<th>Mean difference</th>
<th>95% LoA</th>
<th>Agreement (%)</th>
<th>Mean difference</th>
<th>95% LoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 steps</td>
<td>75.4</td>
<td>−69.3</td>
<td>−182.4 −43.7</td>
<td>83.9</td>
<td>−44.6</td>
<td>−136.1 −46.8</td>
</tr>
<tr>
<td>Day 2 steps</td>
<td>92.6</td>
<td>−23.5</td>
<td>−94.3 −47.2</td>
<td>89.7</td>
<td>−32.5</td>
<td>−141.4 −76.5</td>
</tr>
<tr>
<td>Day 3 steps</td>
<td>98.2</td>
<td>−6.3</td>
<td>−44.4 −31.7</td>
<td>94.4</td>
<td>−18.8</td>
<td>−54.8 −17.2</td>
</tr>
<tr>
<td>Average daily steps</td>
<td>94.1</td>
<td>−21.4</td>
<td>−72.2 −9.0</td>
<td>93.6</td>
<td>−23.5</td>
<td>−82.3 −35.4</td>
</tr>
</tbody>
</table>

LoA = limits of agreement; MC = manual count.

### Table 5

Comparison of Yamax Digiwalker SW-701 pedometer (DIGI) and SenseWear Pro3 Armband (SWA) daily and average 3-day step counts.

<table>
<thead>
<tr>
<th>Variable</th>
<th>DIGI</th>
<th>SWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 steps</td>
<td>11,332 (6855)</td>
<td>12,202* (6551)</td>
</tr>
<tr>
<td>Day 2 steps</td>
<td>9706 (5384)</td>
<td>10,748* (5558)</td>
</tr>
<tr>
<td>Day 3 steps</td>
<td>9438 (5305)</td>
<td>10,596* (5424)</td>
</tr>
<tr>
<td>Average daily steps</td>
<td>10,159 (4227)</td>
<td>11,182* (4439)</td>
</tr>
<tr>
<td>Average step difference</td>
<td>1023* (1288)</td>
<td>11.3%* (11.3)</td>
</tr>
<tr>
<td>Standard error of measurement</td>
<td>673.2</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as mean (SD). * Indicates SWA significantly different from DIGI ($p < 0.05$).
significantly underestimated steps when compared to the step activity monitor (a 2-dimensional accelerometer). It should be noted that participants walked at a lower rate of speed than normal healthy individuals and also used a walking aid as needed. Further research by Furlanetto et al. found that the SWA underestimated steps during treadmill walking at a variety of speeds in a sample including those with chronic obstructive pulmonary disease. All of these findings are similar to the present study, where the SWA significantly underestimated steps when compared to manually counted steps during treadmill walking, particularly at slower speeds. In regard to percent step agreement (Fig. 1), the SWA appears to plateau at faster walking speeds. Raw step counts continued to increase with increases in walking speed and SEM was slightly higher for the fastest treadmill speed compared to the 80 m/min and 94 m/min stages. The step-counting accuracy of the SWA may peak at these moderate speeds of 80 m/min and 94 m/min.

In Study 2, we compared step counts between the DIGI and SWA and found that the SWA overestimated steps compared to the DIGI during free-living. The relationship was observed over a 3-day period, which allowed us to identify a consistent daily overestimation of steps compared to the DIGI by the SWA of 7.7%, 10.7%, and 12.3% for Day 1, Day 2, and Day 3, respectively. In addition, the 95% LoA between the monitors was wide (from −1501 to 3548). This indicates that the variation between wearers is large, and reflects a great degree of underestimation and (to a larger extent) overestimation of step counts by the SWA compared to the DIGI at the individual level. This type of individual variation can be concerning, for instance, it could misrepresent an individual’s true activity levels, or misrepresent behavior change within interventions. Tierney et al. investigated the accuracy of the SWA in counting steps during activities of daily living in individuals with rheumatoid arthritis. The participants were ambulatory with a maximum of one unilateral walking aid. They were asked to perform various activities that were classified into three categories based on metabolic equivalent of task (METS). The three classes of activities were Class A (3–5 METS), Class B (2–3 METS), and Class C (1–2 METS). When compared to manually counted steps, the SWA underestimated steps during each class of activities which included walking at a self-selected speed, going up and down stairs, getting dressed, reading, washing dishes, cleaning, and folding laundry. These findings are unlike those reported in the present study, as we found that the SWA overestimated steps during free-living compared to the DIGI. It could be that differences between the populations could account for the alternative findings, as our sample was a young adult population free of walking impairments/aids while the sample utilized by Tierney et al. was older (mean age 64.4 years) and some utilized a walking aid.

To our knowledge, this is the first study reporting on the validity of the SWA to count steps during free-living conditions in young adults, making comparisons to other research difficult. The SWA appears to overestimate steps compared to the DIGI in free-living. It may be that individuals tend to move their arms through activities such as lifting weights, talking with their hands, reaching for an item, or performing activities of daily living, such as washing dishes, when steps are not being taken. The potential for over counting steps exists when accelerometers are worn on the arm, due to the potential for arm movement when the body is in a fixed position. Conversely, the same can be true when performing activities requiring the arm to remain in a fixed position, such as when carrying a load from one place to another, or walking and sending a text message, which could lead to undercounting steps. Although not focused on stepping data, St-Onge et al. examined SWA EE validity in free-living conditions and found
that the SWA overestimated EE for less active individuals and underestimated EE for more active individuals. A similar study on EE in children by Arvidsson et al.²⁷ found that the SWA underestimated EE during most higher intensity activities (treadmill walking at ≥4.0 km/h, playing basketball, stationary biking, and stepping on and off a step board). When viewing the results of the current study in conjunction with those above, it seems that the SWA may be overestimating physical activity (steps and EE) in active individuals during free-living conditions. We assume that the SWA may be overestimating steps during free-living compared to the DIGI, as a result of erroneous steps being recorded during more complex modes of activity, when the arms may be moving more than the lower extremities (e.g., resistance training, playing basketball, etc.). However, this is only speculation and further research into this phenomenon is needed. It may be beneficial to conduct a laboratory-based study to evaluate the SWAs ability to count steps where participants perform activities of daily living sessions and one researcher counts steps taken, and another researcher counts steps based on arm movements rather than lower extremity movements. This would provide information on whether the SWA overestimates steps due to the arm-based wear-location. Our findings suggest that further research is warranted prior to utilizing the SWA step count metrics as a method of potential utility in intervention settings.

Limitations of the current study include the lack of a true criterion for free-living conditions. The documented inability of the DIGI to accurately estimate steps at low speeds during treadmill walking is a limitation of using the DIGI as a comparative measure in Study 2. However, the DIGI has been validated elsewhere and is commonly used in free-living settings in research.¹⁷–¹⁹ Our results from Study 1 are limited to the speeds utilized and should not be generalized to other speeds or conditions, such as walking at different grades. Our sample was homogenous and relatively active. Results in a sedentary population may differ. Another limitation of this study includes the potential for participants to perform running activities during free-living. Previous research is inconclusive on the ability of Yamax pedometers to count steps during treadmill running, reporting underestimations of step counts and speed-dependent differences from observed step counts.²⁹ Future studies should consider asking participants to log DIGI step counts before and after aerobic-based ambulatory activities, along with requiring individuals to time stamp the activity on the SWA. The time stamp option offered by the SWA allows wearers to track specific bouts of activity by pressing a button located on the SWA when beginning and concluding an activity. Participants (and researchers) could then look at step counts (along with the other metrics) during that bout of activity. This would allow for the comparison of free-living running step counts between the DIGI and SWA. Strengths of this study included the use of manually counted steps as a criterion in Study 1, and the use of a 3-day free living validation period which allowed us to make observations as to the consistency of the SWA step counts compared to the DIGI over multiple days.

In conclusion, the SWA underestimated step counts during treadmill walking and overestimated steps during free-living compared to the DIGI. The SWA may be registering steps in free-living when steps are not being taken. Due to the ability of the layperson to interpret steps more easily than their ability to interpret metrics such as MVPA/EE,²⁷,³⁰ monitors that offer accurate step counts in addition to higher level metrics may assist laypersons in developing a better understanding of how their stepping activities influence their higher level metrics. The results of this study show that the SWA may not accurately estimate steps during treadmill walking or in free-living conditions. Further modifications to the SWA may be warranted to improve the validity and reliability of the SWA step count metrics.

**Conflicts of interest**

There are no conflicts of interest to report.

**Funding/support**

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**References**

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