# Validation of Two Novel Monitoring Devices to Measure Physical Activity in Healthy Women

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*Abstract*— **Measurement of physical activity is increasingly important in health research. We sought to determine the accuracy and sensitivity to non-exercise activity of three activity monitors worn simultaneously by healthy adult women participating in a structured activity protocol. Ten normal-weight women wore the Intelligent Device for Energy Expenditure and Activity (IDEEA), the SmartShoe, and the SenseWear Armband, during activities that included standing, sitting still, sitting and fidgeting, lying down, and walking at varying speeds. Percentage of time postures correctly identified was determined for the IDEEA and the SmartShoe, and activity counts collected from all three devices were compared. Posture was detected with high accuracy by both the IDEEA and the SmartShoe (97.4% and 94.2% accuracy, respectively). The SmartShoe showed superior sensitivity to movement while seated ("fidgeting") compared with the IDEEA (p=0.004 and 0.049 difference between postures, respectively); all three devices distinguished between fast and slow walking. Data support the ability of the IDEEA and the SmartShoe to recognize basic postures in healthy normal-weight women, as well as to detect fidgeting within the seated position.**

## I. Introduction

While exercise has long been known to play an important role in health and fitness, awareness is increasing in recent years of the health impact of non-exercise activity as well. Specifically, energy expenditure related to "active" postures (walking, standing), activities of daily living, and movements such as fidgeting, termed Non-Exercise Activity Thermogenesis (NEAT), are thought to play a role in weight regulation and may distinguish lean from obese individuals [1], [2]. Such activity likely plays a role in disorders of underweight such as Anorexia Nervosa, possibly contributing to difficulty with weight gain encountered by some patients and to susceptibility to relapse [3].

Technology to measure non-exercise activity is evolving. The doubly labeled water method has been a "gold standard" for estimation of free-living total daily energy expenditure, from which NEAT may be derived, but provides little information about patterns or types of activity, and is too cost-prohibitive and not feasible for large-scale studies and routine use. Accelerometers are less obtrusive and show utility in collecting quantitative information about physical activity, but similarly provide limited qualitative data, and underestimate movement of body regions to which they are not attached. More information is provided by wearable devices such as the Intelligent Device for Energy Expenditure and Activity (IDEEA) [4] and SmartShoe [5].

The IDEEA features 5 piezo-electronic sensors attached to the feet, thighs and chest that transmit data about position and acceleration via small wires to a microcomputer worn on the waistband. Data are downloaded to a computer and analyses categorize activity in 32 different compartments, including type of activity as well as its intensity and duration. The IDEEA has been validated in various populations for recognition of physical activity types and for energy expenditure [4], [6], as well as gait parameters [7]. However, no information to our knowledge is available about its ability to detect "fidgeting" movement, i.e., movement within a stationary position, *per se*.

The SmartShoe is a sneaker fitted with an accelerometer on the rear and pressure sensors beneath an insole [5], [8]. Data are wirelessly transmitted via Bluetooth and logged on a smartphone. This monitor categorizes activities as standing, sitting, or walking. Within each posture, acceleration is measured to provide an assessment of movement. Thus, "fidgeting" can be assessed as acceleration from both feet during seated (and standing) positions. SmartShoe has been validated for posture recognition [5], [9] and determination of energy expenditure [8] in small groups of healthy and post-stroke individuals.

The SenseWear Armband (SWA) features a 2-axis accelerometer, heat flux sensor, galvanic skin response sensor, skin temperature sensor, and a near-body ambient temperature sensor. The SWA has been previously validated for measurement of energy expenditure[10], [11].

The current study was conducted with the aim of validating both the IDEEA and the SmartShoe for use in recognition of basic postures and movement while seated in normal-weight women. We focused on women because the primary interest of the Columbia research group is eating disorders, to which women are more susceptible. The SWA was included among the devices to determine comparability in detection of total physical activity across devices worn on different locations on the body.

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## II. METHODS

### A. Participants

Participants were 10 healthy normal-weight women recruited for participation in research studies at the New York State Psychiatric Institute (NYSPI) through local media. Age was 25.3 (SD=3.37) years and BMI was 21.49 (SD=1.43) kg/m$^2$. Exclusion criteria included need for orthotics and inability to participate in moderate-level physical activity, or shoe size less than 6.5 or greater than 9.5. All participants provided written informed consent. The study procedures were approved by the Institutional Review Board of the NYSPI (protocol #5544).

All procedures were conducted at the NYPSI in a study room equipped with a desk and chair, a bed, and a treadmill. Procedures were conducted either in the morning (10 am – 12pm) or afternoon (2pm – 4 pm). A portable DVD player was used to play a TV sitcom to minimize participant boredom. Research staff members were present in the room with participants throughout all study procedures (approximately 1 hour and 45 minutes per participant).

Upon entry to the study room, participants were fitted with the three activity monitors. The IDEEA was placed per protocol[6] with leads adhered to legs, feet, and chest using medical tape. Calibration using a laptop computer was conducted in the upright seated position. The SWA was placed on the upper right arm, and each participant was provided a SmartShoe closest to her shoe size (sizes 7, 8 and 9 were available). Data collection for the SmartShoe was initiated using the hand-held PDA device. Timing for the three different monitors was standardized to the nearest second using the laptop computer (IDEEA and SWA) and PDA for the SmartShoe. The armband was time-stamped at the start and stop of each activity.

### B. Protocol

The activity protocol included five different types of activity, including four static postures: lying down, sitting still, sitting with fidgeting, standing still; and walking, for 8 of 10 participants. (The first two participants did "standing with fidgeting" instead of lying down, with the aim of determining whether fidgeting in this posture could be distinguished from standing still. "Standing with fidgeting" was replaced with lying down, however, after participants showed difficulty fidgeting in the standing position.)

Each participant was assigned to a randomized sequence of non-walking activities, which were performed once before the walking trials and again in reverse order afterwards. The duration of each activity trial was 6 minutes and participants were cued by the study investigator to begin each new activity. Participants were provided guidelines for each activity, including that "fidgeting" while seated should involve movement of legs and/or feet; and that during the "still" postures (sitting still, lying, standing) participants should engage in as little movement as they comfortably could. Walking was performed in a single 18-minute block composed of three consecutive 6-minute blocks of varying speeds in a slow-fast-slow sequence. Speed of walking was, for 8 of 10 participants, 2.0 mph as the slow speed and 2.8 mph as the fast speed; these speeds were comfortable for the majority of our participants. One participant walked at 1.5 and 2.5 mph and one walked at 2.5 and 3.0 mph due to discomfort walking at the standard speeds.

### C. Data Processing and analysis

Data were downloaded using software for each monitor and compiled on an Excel spreadsheet. Data from the SWA were analyzed by using a proprietary algorithm developed by the manufacturer (InnerView™ Professional, Version 6.1, SMT medical technology, Wuerzburg, Germany). Classification of postures and activities, calculation of confusion matrices and assessment of movement in the SmartShoe were performed by scripts written in Matlab (Version 7.5). All data were examined in 60-second epochs. Data collected between the start of a new activity and the start of a minute were discarded, as were data collected towards the end of the six-minute trial that did not fill an entire "clock minute," so that the only 60-second epochs examined were those that were entirely the recorded activity. For each activity type, five full minutes of data were present for each monitor. Device failure occurred for the SWA on one occasion and for the SmartShoe on two occasions; because it was unclear when device failure occurred in the latter, shoe data were discarded from those two participants. All subsequent analyses were conducted using SPSS software (Version 18).

To determine the ability of the IDEEA and the SmartShoe to accurately identify activity type, a confusion matrix was calculated to compare predicted to detected activities across all trials. Each column of the matrix represents the instances in a predicted class, while each row represents the instances in an actual class. One benefit of a confusion matrix is that it is easy to see if the system is confusing two classes (i.e. commonly mislabeling one as another). The SmartShoe was not programmed to detect lying down and thus only standing, walking and sitting were included in analyses for this device.

To determine the ability of each device to detect movement within a given posture, paired t-test was used to assess whether differences were present between "sitting still" and "sitting/fidgeting" and between "walking slow" and "walking fast." Trials in which devices were less than 95% accurate at detecting the trial activity were excluded from this analysis. Thus, from the walking analyses, two additional participants were dropped for the IDEEA, and one additional participant for the SmartShoe.

Intensity of movement was coded for each device as follows: for the IDEEA, number of "counts" per minute in each posture was used across activities; for the seated activities, we also examined "change counts per minute" for the IDEEA, an index of the number of "changes" detected by the device in a given position, to determine whether this might be a more sensitive measure to fidgeting. For the SmartShoe, standard deviation of acceleration from each of the 3 dimensions from the L shoe and the R shoe were averaged to obtain a single number for each of the 5 minutes of data for a given activity trial. That number was then averaged across the 5 minutes and converted to units of acceleration $m/s^2$. For the SWA, "Steps" per minute were used as a measure of activity.

Paired t-test was used to compare activity while sitting still and sitting while fidgeting, and slow and fast walking, so that each individual served as her own control. To determine whether any of the devices systematically measured any of the five postures differently from the first to the second trial, paired t-test was also conducted to compare activity measures taken the first time the participant performed each activity and the second time the participant performed the activity.

To determine the degree to which the different monitors agreed in their detection of inter-individual variability and inter-trial variability in movement intensity, Pearson correlation coefficient was calculated for activity or acceleration measures provided by each device for each of the 10 participants at each of the two trials, for both fidgeting measures and separately for walking measures.

## III. Results

Accuracy of identification of postures and activity types varied by device and by activity type. Overall, both the IDEEA and the SmartShoe each showed excellent accuracy in identifying activity types performed. Table I shows the calculated accuracy of these devices, using individual measures collected across participants.

Fidgeting while seated was detected by the Activity Shoe as distinctly greater activity compared with sitting still (Table II). The IDEEA showed a trend toward greater activity in the fidgeting condition compared with sitting still in "counts per minute" and a significant difference in "change counts per minute" measured during each of these postures, while the SWA did not detect difference between these two activities.

All three devices distinguished "fast walking" from "slow walking".

## IV. Discussion

We report high accuracy for both the IDEEA and the SmartShoe in measurement of basic postures and movement in a structured activity protocol among healthy women. This study represents the first investigation, to our knowledge, comparing accuracy and sensitivity of the IDEEA and the SmartShoe. This is also the first attempt, to our knowledge, to measure "fidgeting" or movement within a particular posture using these devices. Implications of our findings and study limitations are discussed below.

The largest previous study assessing accuracy in activity classification using the IDEEA was conducted in a population of both men and women across a range of ages: the participants engaged in a structured activity protocol including walking, running, stair climbing and descending; sitting, standing, and limb movement. This group reported correct identification rates averaging 98.9% for posture and limb movement type and 98.5% for gait type; pooled correlation between predicted and actual speeds of walking was high in this study [6] (r = 0.986, p<=0.0001). The 97.4% accuracy reported here for postural recognition is consistent with these findings.

In our study, two of the four cases in which less than 95% or poor accuracy was observed for the IDEEA in identification of walking postures occurred when the participant walked at

TABLE I. Accuracy of Identification of Activity Type for the IDEEA and SmartShoe

A) IDEEA

| Actual Class | Predicted class | | | | | |
|---|---|---|---|---|---|---|
| | **Sit** | **Stand** | **Walk** | **Lay** | **Other / transition** | **Class-Specific Recall** |
| **Sit** | *218* | *0* | *0* | *0* | *5* | 0.98 |
| **Stand** | *0* | *116* | *0* | *0* | *0* | 1.00 |
| **Walk** | *0* | *10* | *146* | *0* | *0* | 0.93 |
| **Lay / Recline** | *0* | *0* | *0* | *80* | *0* | 1.00 |
| **Other / Transition** | *0* | *0* | *0* | *0* | *0* | |
| **Class-Specific Precision** | 1.00 | 0.92 | 1.00 | 1.00 | 0 | **0.973** |

B) SMARTSHOE

| Actual Class | Predicted class | | | Class-Specific Recall |
|---|---|---|---|---|
| | **Sit** | **Stand** | **Walk** | |
| **Sit** | *201* | *0* | *2* | 0.99 |
| **Stand** | *4* | *102* | *0* | 0.96 |
| **Walk** | *20* | *0* | *121* | 0.86 |
| **Class-Specific Precision** | 0.89 | 1.00 | 0.98 | **0.942** |

TABLE II. Activity Measures for the IDEEA, SmartShoe, and SWA*

| Device | Lying | Sitting Still | Sitting with Fidgeting | Standing Still | Walking | |
|---|---|---|---|---|---|---|
| | | | | | **Slowly** | **Rapidly** |
| **IDEEA** Counts/ min | 0.20 | 3.391[1] (6.44) | 13.61[1] (13.24) | 0.60 (0.89) | 89.59[4] (6.13) | 110.1[4] (9.0) |
| Change counts/ min | | 1.16[2] (2.58) | 6.73[2] (6.62) | | | |
| **Smart-Shoe** | N/A | 0.148[3] (0.02) | 1.49[3] (0.80) | 0.11 (0.006) | 4.33[5] (0.50) | 6.89[5] (0.80) |
| **SWA** | 0.07 (0.18) | 0.167 (0.25) | 3.01 (6.19) | 0.11 (0.22) | 34.74[6] (26.4) | 75.69[6] (34.6) |

* Units are means (SD) of: "counts" per minute (IDEEA); m/s2 (SmartShoe); "steps" per minute (SWA). Change counts were measured only during sitting. Because of missing data, data for some devices and activities were available from fewer than 10 participants.

1Paired t-test: t[df=9] = 1.966, p = 0.081

2Paired t-test: t[df=9] = 2.278, p = 0.049

3Paired t-test, t[df=6] = 4.428, p = 0.004

4 Paired t-test, t[df=8] = 7.642, p < 0.001

5 Paired t-test, t[df=6] = 11.148, p < 0.001

6 Paired t-test, t[df=8] = 5.463, p = 0.001

the 1.5 mph speed. In fact, these were the only two trials in which participants walked at that particular pace. Thus it is likely that the ability of the IDEEA to detect walking is speed-dependent. The other two mis-identifications of walking by the IDEEA occurred within a single participant for whom significantly less movement was detected by the SWA as well during this activity, despite no visible abnormalities in her gait. Thus it is also possible that certain individuals have gait patterns that are not as easily identified as "walking". (In the latter individual, the IDEEA reported "standing with feet moving" instead of walking.)

The 94.2% accuracy of detecting three major postures/activities by the SmartShoe was comparable to that observed in previous studies (98.1% in healthy individuals [5] and 95% in individuals post-stroke [9]). It should be noted that the posture and activity classification model used in this study was developed from sensor data collected in a study [5] which featured a different acceleration sensor. These changes in the sensor hardware can potentially explain somewhat lower accuracy than previously observed. The classification model also did not include lying down as it is uncommon to lie with the shoes on.

This is one of only a small number of studies to report assessment of movement in the seated position *per se* as a parameter of investigation [12], and the only study to our knowledge to describe its measurement using devices sensitive to the position of the participant as well as to the magnitude of activity -- in other words, both the IDEEA and the SmartShoe detect that the participant is seated, and both devices (particularly, with the IDEEA, using the "change counts per minute" measure), clearly distinguished movement within the seated position from sitting quietly. This advance over devices insensitive to position is critical, because it permits automation of activity monitoring with minimal burden to participants or to researchers. It is also critical because a growing body of evidence shows the inadequacy of inter-rater reliability in assessing non-exercise activity [3], and the inferiority of self-report measures of physical activity as compared with objective assessments [13], [14]. Not surprisingly, the SWA did not capture movement while seated at the parameters set, though it was able to detect differences in walking intensity, and showed a high degree of association with the other monitors on this measure. Further study is required to determine whether fidgeting at different intensities can be measured in a graded fashion with the IDEEA and the SmartShoe, and to confirm that energy expenditure associated with this activity is also correctly identified by the devices. Measurement of fidgeting behavior should prove important in the study of disorders of weight regulation and movement, including understanding of genetic influences on and clinical effects of different levels of non-exercise activity [2]. Such measurement should also advance treatment by helping to promote, either more or less non-exercise activity, as in the case of disorders of overweight and underweight, respectively.

Limitations of this study include relatively restricted activity protocol and somewhat limited sample size, sufficient, however, to demonstrate feasibility of using the IDEEA and the SmartShoe for measurement of NEAT from fidgeting. A future study on a larger population of participants performing less restricted or unrestricted activities will be necessary to fully compare performance of these physical activity monitors.

## V. Conclusion

Data support the ability of the IDEEA and the SmartShoe to recognize basic postures in healthy normal-weight women, as well as to detect fidgeting within the seated position. These results thus support use of both devices in future research investigating non-exercise activity.

## References


[1] J. A. Levine, L. M. Lanningham-Foster, S. K. McCrady, A. C. Krizan, L. R. Olson, P. H. Kane, M. D. Jensen, and M. M. Clark, "Interindividual variation in posture allocation: possible role in human obesity," *Science*, vol. 307, no. 5709, pp. 584–586, Jan. 2005.

[2] D. L. Johannsen and E. Ravussin, "Spontaneous physical activity: relationship between fidgeting and body weight control," *Curr. Opin. Endocrinol. Diabetes Obes.*, vol. 15, no. 5, pp. 409–415, Oct. 2008.

[3] A. Mazloum, M. Johnston, M. Lundrigan, and C. L. Birmingham, "The interrater reliability of rating non-exercise activity of inpatients with eating disorders using a visual analogue scale," *Eat. Weight Disord. EWD*, vol. 13, no. 4, pp. e100–102, Dec. 2008.

[4] K. Zhang, F. X. Pi-Sunyer, and C. N. Boozer, "Improving energy expenditure estimation for physical activity," *Med. Sci. Sports Exerc.*, vol. 36, no. 5, pp. 883–889, May 2004.

[5] E. S. Sazonov, G. Fulk, J. Hill, Y. Schutz, and R. Browning, "Monitoring of Posture Allocations and Activities by a Shoe-Based Wearable Sensor," *Biomed. Eng. IEEE Trans. On*, vol. 58, no. 4, pp. 983–990, 2011.

[6] K. Zhang, P. Werner, M. Sun, F. X. Pi-Sunyer, and C. N. Boozer, "Measurement of human daily physical activity," *Obes. Res.*, vol. 11, no. 1, pp. 33–40, Jan. 2003.

[7] N. A. Maffiuletti, M. Gorelick, I. Kramers-de Quervain, M. Bizzini, J. P. Munzinger, S. Tomasetti, and A. Stacoff, "Concurrent validity and intrasession reliability of the IDEEA accelerometry system for the quantification of spatiotemporal gait parameters," *Gait Posture*, vol. 27, no. 1, pp. 160–163, Jan. 2008.

[8] N. Sazonova, R. Browning, and E. Sazonov, "Accurate Prediction of Energy Expenditure Using a Shoe-Based Activity Monitor," *Med. Sci. Sports Exerc.*, vol. 43, no. 7, pp. 1312–21, Jul. 2011.

[9] G. D. Fulk and E. Sazonov, "Using Sensors to Measure Activity in People with Stroke," *Top. Stroke Rehabil.*, vol. 18, no. 6, pp. 746–757, 2011.

[10] D. L. Johannsen, M. A. Calabro, J. Stewart, W. Franke, J. C. Rood, and G. J. Welk, "Accuracy of armband monitors for measuring daily energy expenditure in healthy adults," *Med. Sci. Sports Exerc.*, vol. 42, no. 11, pp. 2134–2140, Nov. 2010.

[11] G. J. Welk, J. J. McClain, J. C. Eisenmann, and E. E. Wickel, "Field validation of the MTI Actigraph and BodyMedia armband monitor using the IDEEA monitor," *Obes. Silver Spring Md*, vol. 15, no. 4, pp. 918–928, Apr. 2007.

[12] M. Karabulut, S. E. Crouter, and D. R. Bassett Jr, "Comparison of two waist-mounted and two ankle-mounted electronic pedometers," *Eur. J. Appl. Physiol.*, vol. 95, no. 4, pp. 335–343, Oct. 2005.

[13] A. A. van Elburg, H. W. Hoek, M. J. H. Kas, and H. van Engeland, "Nurse evaluation of hyperactivity in anorexia nervosa: a comparative study," *Eur. Eat. Disord. Rev. J. Eat. Disord. Assoc.*, vol. 15, no. 6, pp. 425–429, Nov. 2007.

[14] A. Luke, L. R. Dugas, R. A. Durazo-Arvizu, G. Cao, and R. S. Cooper, "Assessing physical activity and its relationship to cardiovascular risk factors: NHANES 2003-2006," *BMC Public Health*, vol. 11, p. 387, 2011.