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An accelerometer-based earpiece to monitor and quantify physical activity

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Abstract

Background—Physical activity is important in ill-health. Inexpensive, accurate and precise devices could help assess daily activity. We integrated novel activity-sensing technology into an earpiece used with portable music-players and phones; the physical-activity-sensing-earpiece (PASE). Here we examined whether the PASE could accurately and precisely detect physical activity and measure its intensity and thence predict energy expenditure.

Methods—Experiment 1: 18 subjects wore PASE with different body postures and during graded walking. Energy expenditure was measured using indirect calorimetry. Experiment 2: Eight subjects wore the earpiece and walked a known distance. Experiment 3: Eight subjects wore the earpiece and ‘jogged’ at 3.5mph.

Results—The earpiece correctly distinguished lying from sitting/standing and distinguished standing still from walking (76/76 cases). PASE output showed excellent sequential increases with increased in walking velocity and energy expenditure ($r^2>0.9$). The PASE prediction of free-living walking velocity was, 2.5 ± (SD) 0.18 mph c.f. actual velocity, 2.5 ± 0.16 mph. The earpiece successfully distinguished walking at 3.5 mph from ‘jogging’ at the same velocity ($p<0.001$).

Conclusions—The subjects tolerated the earpiece well and were comfortable wearing it. The PASE can therefore be used to reliably monitor free-living physical activity and its associated energy expenditure.

Keywords

Mobile devices; non-exercise activity thermogenesis; energy expenditure; weight loss

INTRODUCTION

The impact of obesity on global health is without question1[-3] overwhelming. It is generally agreed that low levels of physical activity – particularly sitting (i.e. sedentariness) are important in obesity pathogenesis[4-]6. Thus, devising effective tools to measure physical activity could be useful in combating sedentariness. Even the use of commercial pedometers, which are cheap and easy to use, falls off because of their poor accuracy and precision 7. We therefore are seeking to devise valid tools for measuring physical activity.

A major limitation of measuring physiological variables is that people have to utilize separate hardware and software systems. This greatly limits the use of technology beyond the research setting. To improve adherence with the quantification of human physiological variables one could integrate these sensing technologies into everyday electronic devices, thereby broadening the applications and the impact of these devices. To this end we developed an

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earpiece that detects and quantifies physical activity as measured in acceleration units (A.U.) and is able to predict the associated energy expenditure that could be used with portable music players, cell phones, and similar mobile devices.

There has been a 100-fold increase in the use of earpieces by free-living people in the last decade because of the ubiquitous presence of portable music-playing devices and mobile telephones8. Since ~100 million people use these devices already in the United States [8] and carry them throughout the day, we wondered whether the earpiece could be redesigned to detect and quantify habitual, daily physical activity. If such a technology were valid, it might provide not only a means of improving the amount of information we have with respect to physical activity levels in the population, but also as a means of delivering rewards based upon improved activity levels. In addition to this, the earpiece could also deliver feedback about the wearer's progress as well as motivational messages if so desired. Because day-long walking is the predominant component of non-exercise activity thermogenesis (NEAT) [9]and a major target for health interventions.

We tested three hypotheses; the first was the PASE can reliably and repeatably distinguish between sedentariness and activity; the second was that the PASE is an accurate and precise devise for quantifying physical activity: specifically, walking, jogging, inactivity (sedentariness) whilst the third was that the PASE can reliably predict energy expenditure associated with physical activity. Thus, our aims were to examine the reliability, accuracy and precision of the PASE and, secondarily, examine the application of the data to predict activity energy expenditure.

MATERIALS AND METHODS

Description of Physical-Activity-Sensing-earpiece

We devised an earpiece (6 × 6 × 1.45 mm) (that incorporates a micro electro mechanical system (MEMS)) tri-axial accelerometer (MMA7260Q; Freescale Semiconductor, Austin, Texas) with a dynamic range set at ± 2g, which gathers data on three axes of movement, @ 10 Hz. The earpiece fits into the ear in the normal way (Figure 1(A)) and feeds into a 40 g data logging system we devised. After low-pass filtering, the incoming data stream from the three axes are integrated by calculating the sign-corrected sum of the corrected displacements and summating them

Equation 1: Acceleration = $\sqrt{} \, (X_g^2 + Y_g^2 + Z_g^2) - 1$;

Equation 2: $AU^{earpiece} = (\sum_{n=60}(abs(Acceleration_2 - Acceleration_1))/60$;

The earpiece functions with respect to listening to music or a cell phone in a normal way.

The data are acquired and stored on flash memory (SD card) using an Advanced Reduced Instruction Set Computer (RISC) Machine (ARM) microcontroller LPC2138 (Phillips, Eidenhoven, Netherlands) using a program written in ‘C –programming language’. An initiation time stamp is used at the commencement of data collection. The data logging unit (6.5 × 4 × 1.2 cm, 38g) is optional as the earpiece can plug directly into a portable device (via the serial port) such as PDA.

The acquisition event loop (Figure 1(B)) demonstrates that unit is controlled using a custom real-time software application program designed for the ARM. The earpiece configurations can be written on to a simple text file named ‘logcon.txt’ where a series of configurations can easily be defined.

The configuration file can be modified on a PC and then uploaded onto an SD card after which it can be inserted into the earpiece unit. When the ON button is pressed, the unit uploads the configuration onto the device and starts recording data as per the settings in the configuration file.

Experimental Design

Experiment #1—Subjects: 18 healthy, sedentary volunteers were recruited; nine were lean (BMI <25 kg/m^2) and nine were obese (BMI>29 kg/m^2) (Table 1). Subjects were excluded if they smoked, were pregnant, had any acute or chronic illness, had unsteady body weight (>2 kg fluctuation over the six months prior to study), had a medical history of thyroid dysfunction or were taking medications capable of altering metabolic rate. Subjects provided informed written consent and the Mayo Institutional Review Board approved the study.

The objective of Experiment #1 was to ascertain reliability of energy expenditure as predicted by the earpiece as against energy expenditure measured by the indirect calorimetry. The study was conducted in a purpose built room at the Mayo Clinical Research Unit, which contains evaluation equipment and is temperature-controlled and quiet. The subject was orientated to the procedures and then weighed on a calibrated standing scale (model 644, Seca Corporation, Hanover, MD, USA), height was measured using a stadiometer (Model 242, Seca Corporation, Hanover, MD, USA). Subjects were asked to abstain from taking alcohol for at least 12 hours prior to the start of the study. Subjects fasted, had not undertaken exertional activity and had not consumed caffeine for >6 hours. Throughout the study, subjects were in thermal comfort (68−74 °F; 20−23 °C). Subjects placed a Physical-Activity-Sensing earpiece in both their right and left ear, to collect data in duplicate.

Out of total eighteen subjects, twelve subjects (7 women, 5 men; 29 + 12 years; 81 + 20 kg) also wore a physical activity monitoring system (PAMS). This validated system allows body posture and physical activity to be measured every half second continuously and has been validated against both room calorimetry and doubly labeled water in free-living subjects (as opposed to the laboratory-based studies cited above) [9–13]. The PAMS involves wearing Lycra-spandex ® undergarments into which are integrated four inclinometers (Crossbow Technology, Inc, San Francisco, CA) that measure body angle on the right and left lateral aspect of the torso, and the right and left lateral aspect of the mid-thigh. In addition, there are two accelerometers (Crossbow Technology, Inc, San Francisco, CA) placed at the base of the spine. There are two data loggers (Crossbow Technology, Inc, San Francisco, CA) worn around the waist. The PAMS weighs ~1000 grams.

Relaxed subjects lay supine with their head at a 10° tilt. First subjects rested for 30 minutes and then resting energy expenditure was measured for 30 minutes. Subjects were supervised and asked (and prompted where necessary) to remain awake and still during the measurement. The excursions in energy expenditure associate with rest and sitting cannot be conducted reliably even after minimal exertion has occurred and hence the order of activities was fixed and standardized throughout the experiment, as follows.

Energy expenditure was then measured for 20 minutes each under the following conditions:

a. Chair sitting. Subjects were seated in a backed, armed office-chair with their back, arms and legs supported. Subjects were asked to remain relaxed during the measurement.

b. Standing motionless. Subjects were instructed to stand motionless with arms hanging by their sides and feet spaced 6 inches apart. Subjects were asked to remain relaxed and still during the measurement.

c. Walking energy expenditure was then measured for 15 minutes each at 0.5, 1, 1.5, 2, 2.5 and 3 mph whilst subjects walked on a calibrated treadmill (True 600, O'Fallon, MO, USA). Subjects then rested for 15 minutes.

Experiment #2—Subjects: the inclusion criteria were same as for Experiment #1. Here eight healthy, sedentary volunteers were recruited (four women, four men; 30 ± 10 years, 87 ± 21 Kg).

The objective of Experiment #2 was to prospectively test the unifying regression equations that were derived in Experiment #1 to evaluate the ability of the earpiece to predict the walking velocity. Eight volunteers stood motionless as described above for 15 minutes. Subjects were then asked to walk a ¼ mile, indoors or outdoors wearing shoes of their choice at a self-selected velocity. The walking velocity over this measured distance was independently measured by a blinded investigator (blinded to the earpiece output) using paired timers. The accuracy of the earpiece prediction of free-living walking velocity could then be compared to the actual walking velocity.

Experiment #3—Subjects: the inclusion criteria were same as for Experiment #1 except that subjects had to be able to run unencumbered. Here another eight healthy, lean sedentary volunteers were recruited (four women, four men; 38 ± 11 Years, 66 ± 8 Kg).

The objective of Experiment #3 was to examine the sensitivity of the earpiece system to detect the transition from walking at 3.5 mph to jogging at the same velocity. Subjects were asked to stand motionless for 2 minutes, and then walk at 3.5 mph for 2 minutes on a calibrated treadmill. At the end of this period, they were asked to jog at 3.5mph on the treadmill. The goal here was to ascertain whether the physical- activity-sensing-earpiece is sensitive enough to distinguish the change in gait while transitioning from walking to jogging even at same velocity.

Indirect Calorimetry

Measurements of energy expenditure were performed using a high precision indirect calorimeter which is a laboratory 'gold-standard' for measuring energy expenditure (Oxymax H; Columbus Instruments, OH)) [9], as described previously. Expired air was collected using a full-face transparent dilution mask (Scott Aviation, Lancaster, NY connected to the calorimeter by leak-proof tubing (Vacumed, Ventura, CA). We have found that while wearing this equipment, volunteers can complete tasks inside and outside the laboratory such as walking on level ground, climbing stairs in stairwells, or working in an office environment, and even in these circumstances highly precise measures of energy expenditure can be made14.

For the indirect calorimeter, repeated alcohol burn experiments yielded CO_2 and O_2 recoveries of >98%. The SD of the respiratory quotient for the last 15 minutes of the resting measurements was <1% of the mean.

Statistical analysis

Mean energy expenditure for each 20 and 15 minute activity was calculated. All values are provided as mean ± SD. ANOVA (energy expenditure, age, sex, and BMI) and post-hoc paired *t*-tests were used to compare changes in energy expenditure for the 18 subjects. To examine the primary hypothesis that the accelerometer containing earpiece can reliably detect and quantify walking from sedentary postures, we compared the posture predicted by the earpiece with absolute determinations such as walking velocity and visualized body posture determined by PAMS. The proportion of correct allocations for the earpiece was compared using descriptive statistics such as regression and determination of error analysis. To examine whether the earpiece could reliably quantify walking velocity, regression analyses were used comparing the earpiece against actual walking velocity and against that defined by PAMS. Statistical significance was defined as, $p<0.05$.

RESULTS

Bench testing

By definition, when the earpiece is orientated parallel to gravity, the maximal gravitation acceleration is detected (1G). When the earpiece is rotated (i.e., angle of inclination), the earth's gravitation field exerts its force at a tangent and so the measured acceleration decreases.

In our bench testing experiments, with the sensor in the angle (inclinometer) configuration, the measured earpiece angle *versus* the actual angle showed an r^2 of >0.99. In accelerometer configuration, all voltage displacements in x, y and z axes were sign-corrected and summed. There was a near-perfect match (r^2 of ≥0.99) between detected acceleration values and the actual acceleration.

Experiment #1

The earpiece was tolerated well by all subjects, even wearing earpieces in both ears. The reliability of the earpieces was estimated by comparing the right and left earpieces with each other; the mean difference between the earpieces was 0.0034 ± 0.0044 $AU^{earpiece}$ which represented an error of 0.08 ± 0.13% (sign-corrected). In absolute terms, resting energy expenditure, as expected, was significantly less in the lean compare to the obese subjects (Table 1). When expressed relative to body weight, resting energy expenditure was significantly greater in the lean compared to the obese (Table 1). There was a significant positive correlation between weight and resting energy expenditure as expected ($r^2=0.81$, $P<0.0001$).

Posture Detection

In all subjects, the earpiece data correctly distinguished lying from sitting or standing (76/76 cases). Although, an apparent limitation of the earpiece is that it cannot distinguish sitting still from standing still. It is important to note is that the excursion in energy expenditure associated with standing still only represents an increment of 5% over sitting. In this study this represented a maximum error of 8 ± 10 kcal/hr on average, for the lean subjects the error was 8 ± 7 kcal/hr, and for the obese subjects 9 ± 12 kcal/hr.

Activity Detection

In all subjects, the earpiece was able to distinguish walking at ½ mph from standing still (Figure 2(A)). There were progressive increases in earpiece accelerometer output with increasing velocity of walking (Figure 2(B)).

The equation for velocity prediction using output from PASE was:

Equation 3: $\text{Velocity} = 1.079 * AU^{earpiece} - 3.506$

It is important to note that the same regression line cannot be used universally without introducing errors of ±10%. However, progressive increases in earpiece output were seen for all subjects (r^2 ~0.99; range 0.94−1.0).

Energy expenditure increased significantly with each increment in walking velocity regardless of whether energy expenditure was expressed in absolute terms or relative to body weight (r^2 ~0.99 ; $p<0.001$ in all cases). Walking energy expenditure, when expressed in absolute terms, was greater for the obese compared to the lean subjects (Table 1). When walking energy expenditure was expressed relative to body weight, values for the obese subjects were lower than for the lean subjects (Table 1).

The earpiece showed excellent incremental response with respect to detecting walking energy expenditure in both lean and obese participants (Figure 3(A)).

If a single regression equation is used to calculate energy expenditure from earpiece output (EE (kcal/hr/kg) = 0.7865 $AU^{earpiece}$ + 3.6279), the predictive errors introduced are 0.22 ± 4.8 % of energy expenditure. The errors were not significantly different for lean and obese subjects (lean 1.92 ± 4.29 %, obese −1.47 ± 4.65 %).

For the ‘energy expenditure-velocity relationships’, when energy expenditure is expressed in absolute terms, for the lean subjects, slopes were 58 ± 15, and intercepts, 98 ± 25 and for the obese subjects, 85 ± 17, intercept 125 ± 27 (ns) (P=0.002). When expressed relative to weight, the slopes and intercepts for the energy expenditure/weight vs. velocity relationships were for the lean subjects, slope 0.90 ± 0.19, intercepts 1.50 ± 0.19 and for the obese subjects, slope 0.84 ± 0.11 (ns), intercepts 1.23 ± 0.20 (P=0.007) . The areas-under-the-curve for the walking energy expenditure versus velocity curves were for the lean subjects, 412 ± 103 kcal/mph and 6.37 ± 1.11 kcal/kg/mph and for the obese subjects, 602 ± 88 kcal/mph (P<0.001) and 5.96 ± 0.61 kcal/kg/mph.

Furthermore, to validate the physical-activity-sensing-earpiece, we compared the earpieces output with that from a validated physical activity measurement system, PAMS [9]. We found that the earpieces detected sedentary activity and walking bouts with variable intensity with comparable accuracy and precision as PAMS (r^2 ~0.98) (Figure 3(B)).

Experiment #2

We wanted to examine whether the generalized predictive equations for accelerometer output-to-velocity were applicable to predict the free-living velocity akin to subjects walking in a commonplace environment. We used the two regression equations we derived in Experiment #1, one for obese participants and one for lean participants. The earpiece prediction was 2.47 ± SD 0.18 mph compared to the manually measured velocity, 2.46 ± 0.16 mph; the mean sign-correct error for the earpiece was 7.1 ± 5.0 % (Figure 4(A)). These experiments suggest that free-living walking velocity can be predicted reasonably using generalized regression equations.

Experiment #3

In all cases, jogging was readily discernable from walking at the same velocity (3.5 mph). The mean earpiece acceleration whilst standing motionless was 0.015 ± 0.005 $AU^{earpiece}$, whilst walking at 3.5 mph 0.232 ± 0.025 $AU^{earpiece}$ ($p<0.001$ compared to standing). When subjects transitioned from walking to jogging at the same velocity, earpiece acceleration increased to 0.418 ± 0.100 $AU^{earpiece}$ ($p<0.001$ compared to walking) (Figure 4(B)). The earpiece can therefore be used to distinguish the gait of jogging from that of walking.

DISCUSSION

It is widely recognized that low physical activity levels have been associated with the obesity epidemic, both in adults and children [15-19]. A major problem with respect to understanding the role of low physical activity in obesity and reversing this trend has been the difficulty in measuring free-living physical activity [20-22]. We explored the possibility of adapting widely used pre-existing technologies to measure physical activity as a means of not only improving information with respect to free-living physical activity, but also as a step towards reversing low levels of physical activity in the population.

We found that the physical-activity-sensing-earpiece performed well with respect to accuracy and precision. Its specifications matched our pre-existing triaxial accelerometer validated technologies for measuring physical activity[9-12, 23-25]. Although individualized validation of the earpiece improves the accuracy of the walking-velocity prediction, generic regression equations introduced <10% error, albeit in limited laboratory studies of free-living walking. This finding is akin to previous studies [11, 12] but for group-based measurements, generic regression equations are applicable for quantifying human movement. Our studies, therefore suggest that, the earpiece may not only be useful for distinguishing activity from sedentary behaviors but may also be used for quantifying daily activity such as walking, jogging or running. Importantly, this technology could be integrated into an earpiece that is imperceptibly different to a standard earpiece used in portable music players and cell phones. The physical-activity-detecting-earpiece, therefore, has the potential to enable widespread measurement of free-living human activity. Importantly, our data suggest that the earpiece could be useful for monitoring a program of purposeful exercise such as walking or jogging. It is noteworthy that all the data are time-stamped so that bouts of different activities can be identified. Overall, such tools may help combat inactivity and obesity.

The physical-activity-sensing-earpiece also generates new possibilities with respect to promoting physical activity. For example, the earpiece could be used as part of a system to deliver free music downloads to a person once a defined activity threshold is exceeded. In another configuration, we can transmit earpiece-activity data *via* wireless connectivity to a cell phone and so a person in one city can 'compete', activity-wise, with a person in another city. Thus, the activity-sensing earpiece not only has the potential to help measure and detect physical activity but also mediate a reward system that serves to positively reinforce active behaviors.

The physical-activity-sensing-earpiece quantifies all walking at least in the laboratory. In fact, the earpiece was sensitive for detecting even a single step; there was ~300% jump in earpiece output while walking at 0.5 mph as against while standing. The inter-individual prediction of walking energy expenditure was also impressive whereby individual energy expenditure calibration could be used to predict free-living walking energy expenditure. Although the earpiece-accelerometer could be validated against doubly labeled water in future studies, the validation experiments we conducted in the laboratory suggest that the earpiece could potentially measure free-living physical activity with high accuracy and quantify walking and its associated energy cost. It was notable too, that the earpiece showed comparable accuracy and precision to a more expensive and complex detection systems (PAMS, the Physical Activity Monitoring System). This most likely reflects the advancement in micro technological capability; it would not have been possible to produce this hardware configuration a few years ago. Experiments in the free-living state are warranted to further examine the precision and utility of the activity-sensing earpiece in the free-living state.

The experiments we conducted had limitations beyond the fact that they were conducted within a laboratory. The experiments were only conducted in 34 individuals, rather than a broader population. For example, it may be that that elderly individuals have different validation characteristics compared to younger individuals and similarly so for children. Further studies will broaden the scope of our experimental populations. Also, the experiments were short-term in duration. We are excited to extend these studies into the free-living state and conduct doubly labeled water evaluations. Nonetheless, despite the aforementioned limitations, the earpiece can be integrated into everyday electronics and thereby provide new opportunities to expand our knowledge with respect to understanding physical activity in disease and ways to promote more physical activity.

Importantly, we recognize that the earpiece was not tested in free-living people for long periods of time and so we cannot be sure of its long-term acceptability. However, during free-living walking and even jogging all the subjects in all three experiments reported tolerating the earpiece well. It is important to emphasize that earpiece use is already widespread and that the activity-detection technology does not add significant extra weight or discomfort. Thus, physical-activity-sensing-earpiece could be widely used as well.

We do not claim that the earpiece is perfect as the current algorithms do not allow differentiation of specific activities. Importantly there is mounting interest in improving accelerometer algorithms for defining free-living activity [26-28]. As such approaches become accepted; greater capabilities for detecting and quantifying free-living physical activity are likely to emerge. Nonetheless, the data we present suggest that the activity-detecting earpiece can be used to quantify most of the energetically crucial free-living activities. The earpiece in its present configuration is able to readily distinguish sedentariness from activity which is crucially important as sedentariness *per se*, may be a risk factor for morbidity [4, 5, 29] and mortality.

In conclusion, here we describe a Physical-Activity-Sensing earpiece that enables physical activity monitoring to be integrated into a ubiquitous electronic system. By exploiting pre-existing electronic equipment, we anticipate new possibilities for gathering population wide data on physical activity and devising novel strategies to promote active living.

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REFERENCES

1. Wyatt SB, Winters KP, Dubbert PM. Overweight and obesity: prevalence, consequences, and causes of a growing public health problem. Am J Med Sci Apr;2006 331(4):166–174. [PubMed: 16617231]
2. Janssen I, Katzmarzyk PT, Boyce WF, et al. Comparison of overweight and obesity prevalence in school-aged youth from 34 countries and their relationships with physical activity and dietary patterns. Obes Rev May;2005 6(2):123–132. [PubMed: 15836463]
3. Cole TJ, Bellizzi MC, Flegal KM, Dietz WH. Establishing a standard definition for child overweight and obesity worldwide: international survey. Bmj May 6;2000 320(7244):1240–1243. [PubMed: 10797032]
4. Pi-Sunyer FX. Comorbidities of overweight and obesity: current evidence and research issues. Med Sci Sports Exerc Nov;1999 31(11 Suppl):S602–608. [PubMed: 10593535]
5. Spanier PA, Marshall SJ, Faulkner GE. Tackling the obesity pandemic: a call for sedentary behaviour research. Can J Public Health May-Jun;2006 97(3):255–257. [PubMed: 16827420]
6. Blair SN, Brodney S. Effects of physical inactivity and obesity on morbidity and mortality: current evidence and research issues. Med Sci Sports Exerc Nov;1999 31(11 Suppl):S646–662. [PubMed: 10593541]
7. Foster RC, Lanningham-Foster LM, Manohar C, et al. Precision and accuracy of an ankle-worn accelerometer-based pedometer in step counting and energy expenditure. Prev Med Sep-Oct;2005 41(3−4):778–783. [PubMed: 16125760]
8. CTIA. CTIA Survey Year End 2006. 2006. CTIA-The_Wireless_Association®
9. Levine JA, Lanningham-Foster LM, McCrady SK, et al. Interindividual variation in posture allocation: possible role in human obesity. Science Jan 28;2005 307(5709):584–586. [PubMed: 15681386]
10. Levine J, Melanson EL, Westerterp KR, Hill JO. Tracmor system for measuring walking energy expenditure. Eur J Clin Nutr Sep;2003 57(9):1176–1180. [PubMed: 12947439]

11. Levine JA, Baukol PA, Westerterp KR. Validation of the Tracmor triaxial accelerometer system for walking. Med Sci Sports Exerc 2001;33(9):1593–1597. [PubMed: 11528350]
12. Levine JA, Baukol PA, Westerterp K. Comparison of the Tracmor accelerometer output between walking on a treadmill and on level ground. North American Association for the Study on Obesity. 2000
13. Levine J, Melanson EL, Westerterp KR, Hill JO. Measurement of the components of nonexercise activity thermogenesis. Am J Physiol Endocrinol Metab 2001;281(4):E670–675. [PubMed: 11551842]
14. Levine JA, Schleusner SJ, Jensen MD. Energy expenditure of nonexercise activity. Am J Clin Nutr 2000;72(6):1451–1454. [PubMed: 11101470]
15. Obarzanek E, Schreiber GB, Crawford PB, et al. Energy intake and physical activity in relation to indexes of body fat: the National Heart, Lung, and Blood Institute Growth and Health Study. Am J Clin Nutr 1994;60(1):15–22. [PubMed: 8017331]
16. Chad KE, Reeder BA, Harrison EL, et al. Profile of physical activity levels in community-dwelling older adults. Med Sci Sports Exerc Oct;2005 37(10):1774–1784. [PubMed: 16260980]
17. Crespo CJ, Keteyian SJ, Heath GW, Sempos CT. Leisure-time physical activity among US adults. Results from the Third National Health and Nutrition Examination Survey. Arch Intern Med 1996;156(1):93–98. [PubMed: 8526703]
18. Dietz W. Physical activity and childhood obesity. Nutrition 1991;7(4):295–296. [PubMed: 1802224]
19. Hirvensalo M, Rantanen T, Heikkinen E. Mobility difficulties and physical activity as predictors of mortality and loss of independence in the community-living older population. J Am Geriatr Soc May; 2000 48(5):493–498. [PubMed: 10811541]
20. Bonnefoy M, Normand S, Pachiaudi C, Lacour JR, Laville M, Kostka T. Simultaneous validation of ten physical activity questionnaires in older men: a doubly labeled water study. J Am Geriatr Soc Jan;2001 49(1):28–35. [PubMed: 11207839]
21. da Rocha EE, Alves VG, da Fonseca RB. Indirect calorimetry: methodology, instruments and clinical application. Curr Opin Clin Nutr Metab Care 2006;9(3):247–256. [PubMed: 16607124]
22. Goran MI. Estimating energy requirements: regression based prediction equations or multiples of resting metabolic rate. Public Health Nutr Oct;2005 8(7A):1184–1186. [PubMed: 16277827]
23. Harris AM, Lanningham-Foster LM, McCrady SK, Levine JA. Nonexercise movement in elderly compared with young people. Am J Physiol Endocrinol Metab Apr;2007 292(4):E1207–1212. [PubMed: 17401138]
24. Lanningham-Foster LM, Jensen TB, McCrady SK, Nysse LJ, Foster RC, Levine JA. Laboratory measurement of posture allocation and physical activity in children. Med Sci Sports Exerc Oct;2005 37(10):1800–1805. [PubMed: 16260984]
25. Levine JA, Eberhardt NL, Jensen MD. Role of nonexercise activity thermogenesis in resistance to fat gain in humans. Science 1999;283(5399):212–214. [PubMed: 9880251]
26. Crouter SE, Churilla JR, Bassett DR Jr. Estimating energy expenditure using accelerometers. Eur J Appl Physiol Dec;2006 98(6):601–612. [PubMed: 17058102]
27. Crouter SE, Clowers KG, Bassett DR Jr. A novel method for using accelerometer data to predict energy expenditure. J Appl Physiol Apr;2006 100(4):1324–1331. [PubMed: 16322367]
28. Crouter SE, Bassett DR Jr. A New 2-regression Model for the Actical Accelerometer. Br J Sports Med. Aug 30;2007
29. Rosal MC, Ockene JK, Ma Y, et al. Behavioral risk factors among members of a health maintenance organization. Prev Med Dec;2001 33(6):586–594. [PubMed: 11716654]

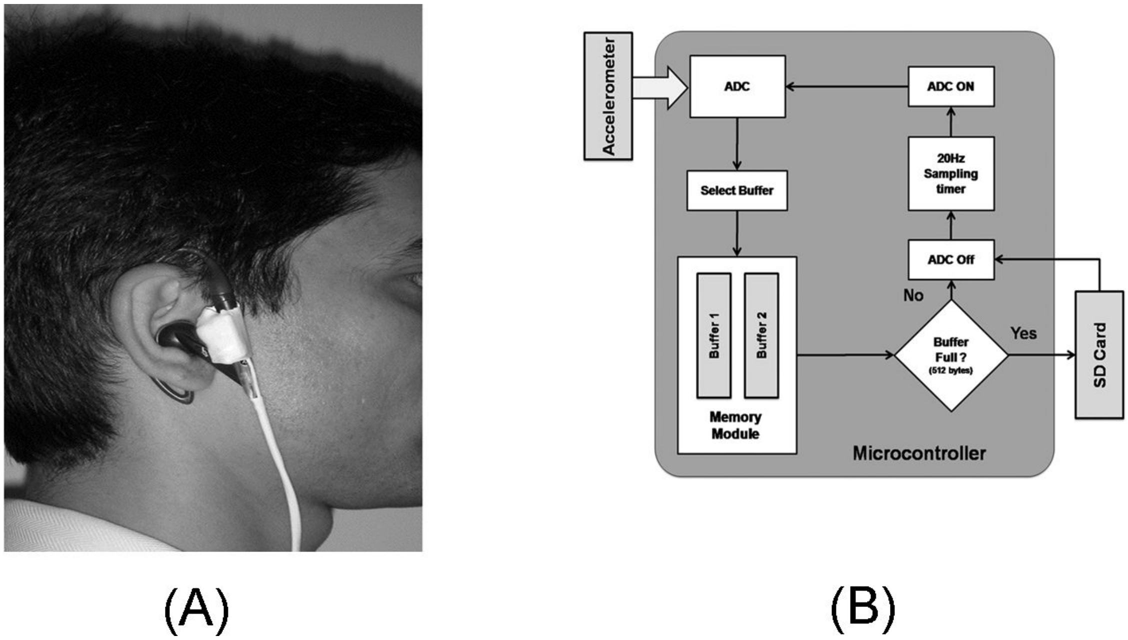


Figure 1.
(A) Physical Activity Sensing earpiece. The current operational prototype incorporates a MEMS tri-axial accelerometer. **(B)** Event Acquisition Loop for the Tri-axial accelerometer based Activity Monitoring earpiece.

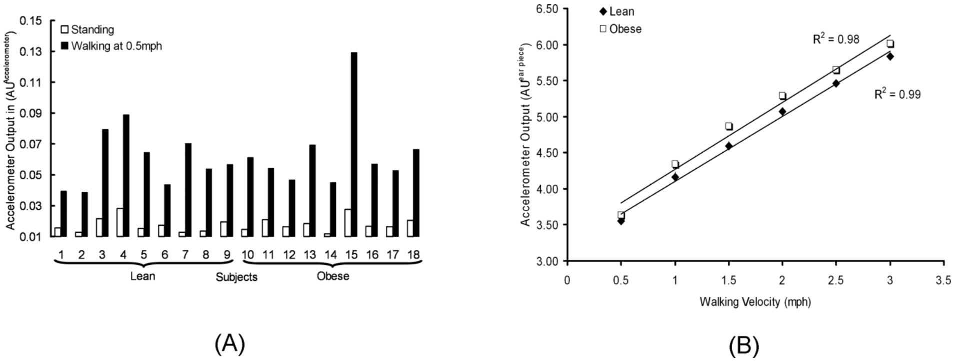
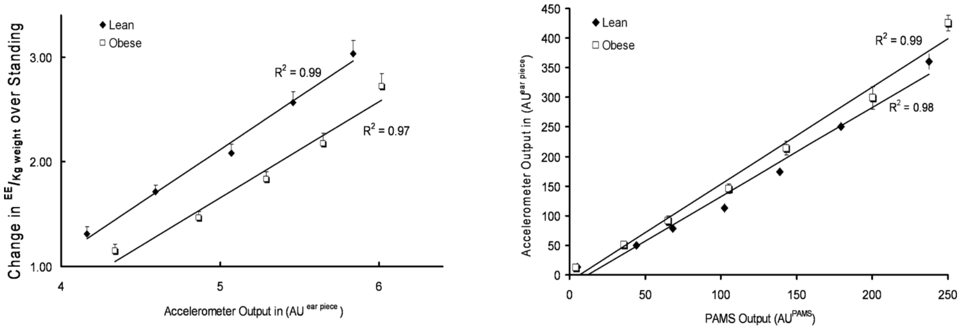


Figure 2.

(A) Earpiece output (AU $^{\text{ear piece}}$) for lean (n=9) and obese (n=9) participants while standing still and walking at 0.5mph. **(B)** Earpiece accelerometer output (AU $^{\text{ear piece}}$) versus walking velocities from 0.5mph to 3.5 mph with 0.5mph increments for lean and obese participants. Data are shown as Mean ± SE.

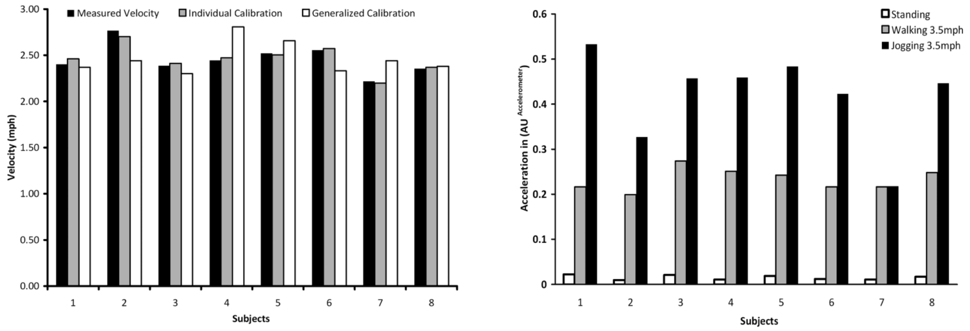


(A)

(B)

Figure 3.

(A) Change in energy expenditure relative to body mass, in Kcal/hr/kg above standing while walking at 1, 1.5 2, 2.5 and 3 mph versus the acceleration, in acceleration units (AU $^{\text{ear piece}}$). **(B)** Earpiece accelerometer output (AU $^{\text{ear piece}}$) versus PAMS accelerometer output (AU $^{\text{PAMS}}$) for 12 subjects. Data are shown as Mean ± SE.



(A) (B)

Figure 4.

(A) Earpiece prediction of walking velocity for 8 subjects walking ¼ mile on a level surface at self-selected velocity. The bar charts show the actual velocity measured using a tape measure and stop-watch, the velocity predicted using an individualized calibration step and the velocity predicted using a generic prediction equation. **(B)** Earpiece acceleration output ($AU^{\text{ear piece}}$) while standing still, walking at 3.5 mph and jogging at 3.5 mph for 8 subjects.

Table 1

Energy expenditures (kcal/hour) for 18 study participants. Data are expressed as mean ± SD. The energy expenditure, when expressed in absolute terms, was greater for the obese compared to the lean subjects while when it was expressed relative to body weight, values for the obese subjects were lower than for the lean subjects.

	TOTAL	**Lean**	**Obese**	**Lean vs. obese**
N (women; men)	18 (9:9)	9 (4:5)	9 (5:4)	
Weight (kg)	83±23	65 ± 14	101 ± 15	P<0.001
BMI (kg/m^2)	28±7	22 ± 3	34 ± 3	P<0.001
Age (± SD) years	27 ± 9	30 ± 10	23 ± 4	NS
Energy expenditure (kcal/hr)				
Resting	76 ± 19	66 ± 14	85 ± 20	0.04
Sitting	87 ± 21	76 ± 16	97 ± 22	0.04
Standing	95 ± 26	84 ± 20	106 ± 29	NS
Walking: 0.5 mph	156 ± 40	137 ± 32	176 ± 39	0.03
Walking: 1 mph	197 ± 53	165 ± 38	228 ± 48	0.007
Walking: 1.5 mph	223 ± 57	189 ± 44	256 ± 49	0.007
Walking: 2 mph	252 ± 67	211 ± 48	293 ± 58	0.005
Walking: 2.5 mph	284 ± 72	240 ± 52	327 ± 64	0.006
Walking: 3 mph	324 ± 87	270 ± 61	379 ± 74	0.004
Energy expenditure/weight (kcal/kg/hr)				
Resting	0.93 ± 0.16	1.02 ± 0.13	0.83 ± 0.14	0.008
Sitting	1.07 ± 0.18	1.18 ± 0.1	0.96 ± 0.18	0.006
Standing	1.16 ± 0.21	1.29 ± 0.13	1.03 ± 0.20	0.005
Walking: 0.5 mph	1.92 ± 0.34	2.10 ± 0.21	1.75 ± 0.36	0.02
Walking: 1 mph	2.39 ± 0.31	2.54 ± 0.29	2.24 ± 0.26	0.03
Walking: 1.5 mph	2.72 ± 0.34	2.91 ± 0.33	2.53 ± 0.25	0.01
Walking: 2 mph	3.07 ± 0.38	3.25 ± 0.36	2.89 ± 0.31	0.04
Walking: 2.5 mph	3.47 ± 0.50	3.72 ± 0.48	3.22 ± 0.40	0.03
Walking: 3 mph	3.96 ± 0.57	4.17 ± 0.56	3.74 ± 0.51	NS