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An artificial neural network to estimate physical activity energy expenditure and identify physical activity type from an accelerometer

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¹Department of Mathematics and Statistics, University of Massachusetts, Amherst, Massachusetts; ²Department of Exercise Science, Lyndon State College, Lyndonville, Vermont; ³Department of Exercise and Health Sciences, University of Massachusetts, Boston, Massachusetts; ⁴Department of Exercise, Sport and Leisure Studies, University of Tennessee, Knoxville, Tennessee; and ⁵Department of Kinesiology, University of Massachusetts, Amherst, Massachusetts

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Staudenmayer J, Pober D, Crouter S, Bassett D, Freedson P. An artificial neural network to estimate physical activity energy expenditure and identify physical activity type from an accelerometer. *J Appl Physiol* 107: 1300–1307, 2009. First published July 30, 2009; doi:10.1152/jappphysiol.00465.2009.—The aim of this investigation was to develop and test two artificial neural networks (ANN) to apply to physical activity data collected with a commonly used uniaxial accelerometer. The first ANN model estimated physical activity metabolic equivalents (METs), and the second ANN identified activity type. Subjects ($n = 24$ men and 24 women, mean age = 35 yr) completed a menu of activities that included sedentary, light, moderate, and vigorous intensities, and each activity was performed for 10 min. There were three different activity menus, and 20 participants completed each menu. Oxygen consumption (in $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) was measured continuously, and the average of minutes 4–9 was used to represent the oxygen cost of each activity. To calculate METs, activity oxygen consumption was divided by $3.5 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ (1 MET). Accelerometer data were collected second by second using the Actigraph model 7164. For the analysis, we used the distribution of counts (10th, 25th, 50th, 75th, and 90th percentiles of a minute's second-by-second counts) and temporal dynamics of counts (lag, one autocorrelation) as the accelerometer feature inputs to the ANN. To examine model performance, we used the leave-one-out cross-validation technique. The ANN prediction of METs root-mean-squared error was 1.22 METs (confidence interval: 1.14–1.30). For the prediction of activity type, the ANN correctly classified activity type 88.8% of the time (confidence interval: 86.4–91.2%). Activity types were low-level activities, locomotion, vigorous sports, and household activities/other activities. This novel approach of applying ANNs for processing Actigraph accelerometer data is promising and shows that we can successfully estimate activity METs and identify activity type using ANN analytic procedures.

signal processing

OBJECTIVE MEASUREMENT OF PHYSICAL activity (PA) in a free-living setting is essential for understanding the determinants of individuals' PA behavior, evaluating the effectiveness of interventions designed to increase PA, performing PA surveillance, and quantifying the relationship between PA dose and health outcomes. Commensurate with the widespread interest in objective PA assessment, there are many wearable devices available for the assessment of free-living PA. Accelerometer sensors, in particular, have been selected as the device of choice; however, data processing methods of accelerometer

output have yet to realize their promise to provide accurate estimates of PA type, patterns, and energy expenditure.

Nearly all applications of accelerometer-based PA monitors to quantify PA have used a similar approach to process and interpret accelerometer data by collecting simultaneous recordings of energy expenditure using direct or indirect calorimetry and accelerometer output. The relationship between the monitor output and energy expenditure is modeled using linear regression techniques to develop a formula either to estimate energy expended in PA (PAEE) or to establish a set of “cut-points” used to determine time spent in different intensity ranges (6, 7, 9, 10, 12, 20, 22). While these approaches have been well received by the scientific community and often result in relatively small or nonsignificant mean differences between estimated and actual PAEE when applied to a large group of subjects, the individual estimation errors are often substantial (2, 16).

The lack of satisfactory results in the comparison of estimated PAEE from PA monitors to actual PAEE is due to the regression not fitting all modes of activity. The regression equations developed from locomotion activities provide poor estimates of energy expenditure for lifestyle activities that involve movement that is not captured by the accelerometer (e.g., upper body movements), and equations developed on lifestyle activities are not valid when applied to locomotion behaviors (1, 21). In an effort to address this concern, variations of the linear regression approach by employing different equations for different types of activity have been proposed (6, 9, 12). Alternatively, use of two sensors simultaneously, such as heart rate and accelerometers and processing data with branched chain equation modeling (3) and cross-sectional time series (24), have also been used in an attempt to improve PAEE estimates. Another common limitation of translating accelerometer data to physiologically meaningful energy expenditure metrics is that the single integrated accelerometer signal averaged over time essentially eliminates the rich features of the accelerometer signal and contributes to the imprecision of the PAEE estimates (17).

Another approach to improve estimates of PAEE is to use pattern recognition or “machine learning” approaches to the processing of data from accelerometers. Our group reported success in applying hidden Markov models (HMM; a type of probabilistic pattern recognition algorithm for times series data) and other statistical classification tools to accelerometer data to identify specific modes of activities (17). Other groups have also had success identifying specific activities by applying different types of pattern recognition algorithms to accelerometer data (5, 14, 15, 21). This may ultimately lead to

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improved estimates of PAEE through the application of activity-specific regression equations to estimate energy expenditure or through identification of specific activities using multiple features of the acceleration signal. Application of an ANN to data from accelerometers to directly estimate PAEE has been reported (19).

While these new approaches to data processing hold promise, each example suffers from some shortcomings that may preclude widespread adoption by researchers. The HMM approach used by Pober and colleagues (17), while appealing from a theoretical standpoint, is relatively complex and relies on custom software that may be a barrier for many applied researchers. Furthermore, it has only been tested on a limited sample and with a limited number of activities and is not yet capable of providing validated estimates of PAEE. The ANN approach described by Rothney et al. (19) has been validated on a much larger sample and with a greater range of activities, but was developed using expensive software (Matlab, Mathworks, Cambridge, MA), and a customized version of the multiple accelerometer IDEEA PA monitor is not practical for large-scale investigations.

We suggest that, if more sophisticated approaches to data processing are to be widely adopted by PA researchers, the methods must apply to data from commonly used activity monitors, and individuals with limited computational and statistical background should be able to use these methods. Thus the purpose of the present study was to develop and validate two separate pattern recognition systems [artificial neural networks (ANNs)]: one to estimate PAEE, and one to estimate activity type. The models use the same inputs, but they are separate: estimates of activity type are not used to estimate PAEE. Using the free and open source computing language and statistics package R (18), we fit two optimized ANNs to data collected using a popular commercially available accelerometer-based PA monitor (Actigraph Model 7164, Actigraph, Pensacola, FL). The first model estimated metabolic equivalents (METs), and the second model identified activity type, and results were compared with actual METs measured using indirect calorimetry and the actual activity type.

METHODS

Subjects and Data Collection

Subject descriptive characteristics and data collection methods for this study appear elsewhere (6–9). Volunteer subjects were included in the study, if they had no contraindications to exercise and were physically able to complete the tasks. Before participating, subjects completed a Physical Activity Readiness Questionnaire and read and signed an approved informed consent document. The procedures were reviewed and approved by the University of Tennessee Institutional Review Board before the start of the study. Twenty-four women and twenty-four men (see Table 1) each completed one to three of the following routines. Two performed all three routines; eight did two routines, and the rest did one routine.

1) *Routine 1*: Lying down, standing still, performing seated computer work, walking upstairs at a self-selected pace, walking downstairs at a self-selected pace, and stationary cycling at a self-selected work rate. Self-selected paces were used to simulate “free-living” activities.

2) *Routine 2*: Walking around a track at ~1.34 m/s (self-paced slow), walking around a track at ~1.79 m/s (self-paced fast), playing one-on-one basketball, playing singles racquetball, running around a

Table 1. *Subject characteristics*

	Men	Women	All
<i>n</i>	24	24	24
Age, yr	36.0 (21–69)	35.0 (22–55)	35.0 (21–69)
Height, in.	70.9 (62.8–72.4)	65.1 (60.2–68.5)	68.0 (60.2–74.2)
Body mass, kg	83.9 (59.4–141.0)	62.3 (45.4–109.0)	73.1 (45.4–141.0)
BMI, kg/m ²	25.8 (19.1–40.6)	22.7 (17.9–36.4)	24.2 (17.9–40.6)
Resting $\dot{V}O_2$, ml·kg ⁻¹ ·min ⁻¹	3.6 (2.1–5.0)	3.4 (2.0–4.9)	3.5 (2.0–5.0)

Values are means with range in parentheses; *n*, no. of subjects. BMI, body mass index; $\dot{V}O_2$, oxygen consumption.

track at ~2.24 m/s (self-paced slow), and running around a track at ~3.14 m/s (self-paced fast). These speeds were self-paced.

3) *Routine 3*: Vacuuming, sweeping and/or mopping, washing windows, washing dishes, lawn mowing with a push mower, and raking grass and/or leaves. Again, these activities were self-paced.

Subjects performed each activity for 10 min, followed by 1–2 min of rest. During the activity sessions, oxygen consumption was measured breath by breath and averaged every 30 s using the Cosmed K4b² (Cosmed, Rome, Italy). The average of minutes 4–9 was used to represent the activity oxygen consumption (in ml·kg⁻¹·min⁻¹), and these values were divided by 3.5 ml·kg⁻¹·min⁻¹ to calculate METs for each activity. PA was monitored using an Actigraph model 7164 accelerometer (Actigraph, Pensacola, FL) mounted in a nylon pouch, secured at waist height over the subject's anterior-axillary line. The accelerometer uses an analog band-pass filter to process the raw measurements of acceleration, and it records 10 digitized measures of acceleration per second. We used 1-s epochs, which record “counts,” the sum of the 10 measurements per second.

Statistical Methods

An ANN is a nonlinear regression model, and, like other regression models, it is used to model the relationship between a response (*y*) and covariates (x_1, \dots, x_p), where *p* is the number of predictors.

We use two different ANNs applied to the accelerometer signals: one to predict METs (*y*) from x_1, \dots, x_p (summaries of the accelerometer signals), and one to identify PA type. Note that the models are completely separate, and the estimates of PA type are not used to predict METs.

We discuss the covariates we actually used and our four PA type definitions specifically below. The general form of the ANN regression model for the METs application is $y = \beta_0 + \sum_{h=1}^H [\beta_{1,h} \phi(\beta_{2,h} + \sum_{k=1}^K \beta_{k+2,h} x_k)] + \text{error}$, where β are coefficients that need to be estimated, $\phi(z) = \exp(z)/[1 + \exp(z)]$ (the logistic function, a special case of the “softmax” function), and *H* is the size of the “hidden layer.”

In the PA type application, let m_1, \dots, m_4 represent the possible activity types. Similar to logistic regression, the ANN we use models $Pr(y = m_i) = C \exp\{\theta_{0,i} + \sum_{h=1}^G [\theta_{1,h,i} \phi(\theta_{2,h,i} + \sum_{k=1}^K \theta_{k+2,h,i} x_k)]\}$, where *C* is chosen so that $Pr(y = m_1) + \dots + Pr(y = m_4) = 1$, and *Pr* means probability. In this case, θ are the unknown parameters, and *G* is the size of the hidden layer. Both of these models are single hidden layer models without skip layer connections.

In general, ANNs are useful for prediction through a two-step procedure. First, a “training” data set consisting of observations of both *y*'s and *x*'s is used to estimate the β . After training, the model is applied to process a data set where only the *x*'s (accelerometer counts and person-specific information) are observed to estimate the *y*'s (METs or PA type). This procedure is similar to the way that regression “cut point” procedures have been used previously.

To use these models, we address the following: 1) definition of *y* and x_1, \dots, x_p ; 2) size of hidden layer; 3) criteria to estimate the β ; and 4) software to implement these methods.

Definition of y and x_1, \dots, x_p . The raw data consist of second-by-second accelerometer counts, demographic information for a person,

average observed METs for each activity and each person, and second-by-second classifications of the activity. In general, there is no optimal way to use these data in an ANN, and we employed several approaches to develop a model that performs well empirically.

For the MET application, y_{it} is the METs for person i during minute t . In the PA type application, we grouped the activities into one of four types, and each y_{it} falls into one of these four categories (See Table 2). We grouped the activities into four activity types instead of predicting actual activity name to improve prediction accuracy.

We determined these groups by clustering the accelerometer signals into four categories: 1) very low mean signals (low level of activity); 2) rhythmic and repeatable signals (locomotion); 3) less rhythmic and lower mean signals (household activities/other); and 4) high variability and high mean signals (vigorous sports) (see Fig. 1, right, for examples). Figure 1, left, illustrates the clustering. For each unique person/activity combination, we computed the mean and SD of the associated counts. The plotted points are coded by activity type. We note that Crouter et al. (8) used a similar idea when they differentiated locomotion from nonlocomotion based on coefficient of variation of the counts. In their case, that differentiation determined which one of two regression models to use to predict METs. In our case, the prediction of METs is done separately with a different neural network that is specialized for that purpose.

We developed covariates (x_1, \dots, x_p) to use two types of input information in the neural network: 1) summaries of the distribution of the counts in 1 min; 2) summaries of the temporal dynamics of the counts in 1 min.

For the first type, we chose the 10th, 25th (Q1), 50th (median), 75th (Q3), and 90th percentiles of a minute's second-by-second accelerometer counts. The middle three summaries are commonly used in box plots to characterize distributions, and the 10th and 90th percentiles are chosen as stable estimates of low or high counts. The ANN is flexible so that it will use the information in combinations of these summaries as well. For instance, since Q3 minus Q1 is approximately proportional to the standard deviation, and the mean is approximately a weighted average of all five summaries, the information in those two common statistics (or their ratio, the coefficient of variation) is included implicitly in these summaries as well.

We also use lag one autocorrelation of the counts in the minute as a measure of temporal dynamics. We model the data on the time scale of minutes so that a minute's worth of accelerometer information is used to estimate the average METs during that minute and the most likely activity type. Table 3 lists the averages of these statistics (in counts per second) for each activity.

These summary statistics were computed after we cleaned the data by removing subject/activity combinations, where the coefficient of variation of the counts was >90% different than the mean coefficient of variation for a particular activity. We recognized that this cleaning step was necessary by visually inspecting plots of counts over time for each subject and each activity. This visual inspection led to the data removal rule. We assumed that these subject/activity combinations

resulted from a malfunctioning activity monitor or some other unknown factors. This resulted in the removal of 13 of 378 (3.4%) subject/activity combinations, and the defective data were not more prevalent for certain activities or subjects. The neural networks did not converge to stable estimates reliably when those data were included. We believe that this was the result of extreme data outliers.

Size of hidden layer and criteria to estimate the β . In general, more terms in the hidden layer mean more β and a more flexible model. Additional flexibility avoids bias, but it can also lead to problems of overfitting, where the model might fit the "training" data very well, but it will perform poorly when used for prediction in a new data set. One approach to decide the size of the model is to try models of various sizes and choose the model that has the best cross-validated estimate of performance. We choose a more flexible approach that uses a large number of hidden units and then find β to minimize the lack of fit statistic (least squares for PAEE and negative log-likelihood for PA type) plus a penalty, $\lambda \sum_{j,h} \beta_{j,h}^2$ (or $\lambda \sum_{j,h} \theta_{j,h}^2$ for the model that estimates activity type). Informally, this penalty imposes a cost on the variability of the β . When $\lambda = 0$, bias is reduced, and overfitting is a danger. When λ becomes large, the β approach zero, and bias becomes a danger. Somewhere between those two extremes, a tradeoff between bias and overfitting is reached, and we chose a λ that achieves the best cross-validated estimate of performance, thereby optimizing that tradeoff. We chose the number of hidden units to be 25 and found that the performance was similar when the number of hidden units was that number or higher. Before fitting the model, the covariates were all centered and scaled by constants, so that each has a range of approximately -1 to 1 . This numerically stabilized the fitting step.

Software to implement these methods. We implemented these methods using the nnet library (23) in R. R is an open-source statistical computing language that has similar capabilities to SAS but different syntax. R and nnet are freely available.

RESULTS

We assessed model performance with the leave-one-subject-out cross validation. For each subject, a model is trained using all but one subject and then tested (see below) on the left-out subject. That "training" involves parameter estimation, not choosing model size or the penalty parameter. After that is completed for all of the subjects, the test results are averaged. This method yields a valid estimate of how well the model would do if it were applied to a population on which it was not trained.

For the METs prediction application, the test consists of computing the mean squared differences between the ANN's prediction and the measured METs for the left-out subject. It should be noted that, when the ANN was developed, it was "trained" on 5-min averages of steady-state energy expenditure. When it is used for estimation though (like other methods), it is applied to minute-by-minute data, which include time periods when individuals are not in steady state and their energy expenditure may fluctuate considerably during intermittent activities. For this reason, we have chosen to evaluate the error in the ANN in two ways: comparing measured and predicted METs after averaging over the activity bout for the individual, and comparing minute-by-minute predictions and steady-state measurements. The errors are smaller in the "per bout" evaluation, since the over- and underestimations from 1 min to the next within an activity tend to cancel each other out.

Figure 2 compares the measured and predicted average METs for each activity bout. The figure compares four algorithms: the ANN, two cut-point methods (10, 20), and the method developed by Crouter and Bassett (6). The minute-by-minute ANN prediction of METs has a root-mean-squared

Table 2. Physical activities and activity category used for activity-type identification

Activity Types			
Low Level of Activity	Household Activity and Other	Locomotion	Vigorous Sport
Activities			
Computer work	Raking	Fast run	Basketball
Filing	Stationary cycling	Fast walk	Racquetball
Lying down	Sweep / mop	Lawn mowing	
Standing	Vacuum	Slow run	
	Wash dishes	Slow walk	
	Wash windows	Walking stairs	

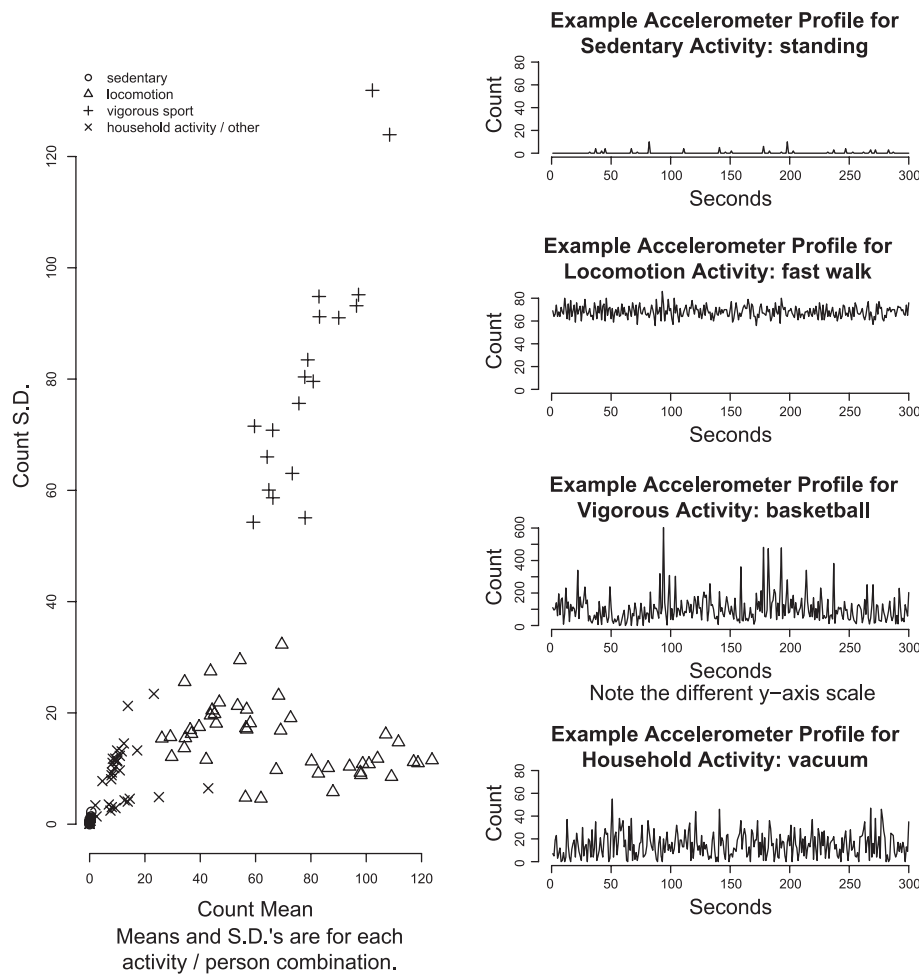


Fig. 1. *Left*: activity types cluster by the mean and SD of the accelerometer counts over 1 min. *Right*: examples of second-by-second accelerometer counts over time.

error of 1.22 METs [confidence interval (CI): 1.14–1.30]. Table 4 illustrates the effect of cycling and contains the by-activity “bout” level comparisons too. Figure 3 compares the minute-by-minute ANN predictions and the measurements. In this figure, the width of each box shows the subject-to-

subject variability in both the measured and predicted METs. In addition, Fig. 4, *top*, shows the subject-to-subject variability of root mean squared error. In this figure, each root mean squared error shows how a model that is trained on all of the other subjects performs on the left-out subject. Figure 5, *top*,

Table 3. *Distribution characteristics and auto correlations for each physical activity*

	10th Percentile	Q1 (25th Percentile)	Q2 (50th Percentile)	Q3 (75th Percentile)	90th Percentile	Lag 1 Autocorrelation
Computer work	0.00	0.00	0.00	0.00	0.04	0.02
Filing	0.00	0.00	0.00	0.09	0.80	0.04
Lying down	0.00	0.00	0.00	0.00	0.02	0.01
Standing	0.00	0.00	0.00	0.07	0.63	0.08
Raking	2.26	6.31	14.07	25.03	38.01	0.21
Stationary cycling	6.92	8.41	10.18	12.15	14.11	0.12
Sweep/mop	0.51	2.64	7.55	16.35	27.35	0.34
Vacuum	1.04	3.25	8.23	16.34	29.15	0.27
Wash dishes	0.00	0.01	0.14	1.21	4.65	0.19
Wash windows	0.03	0.36	1.76	6.60	17.25	0.41
Fast run	119.29	126.59	135.47	145.06	152.60	−0.22
Fast walk	75.68	79.00	82.76	86.48	89.79	0.25
Lawn mowing	18.58	28.74	40.36	51.63	60.53	0.43
Slow run	117.14	126.03	135.59	145.43	152.99	−0.06
Slow walk	49.59	52.63	56.22	59.62	62.49	0.03
Walking stairs	26.52	39.69	52.46	70.18	81.55	0.41
Basketball	20.75	36.96	67.66	120.97	198.85	0.43
Racquetball	8.16	19.87	41.54	79.65	138.85	0.47

Q1, Q2, Q3: first, second, and third quartile, respectively.

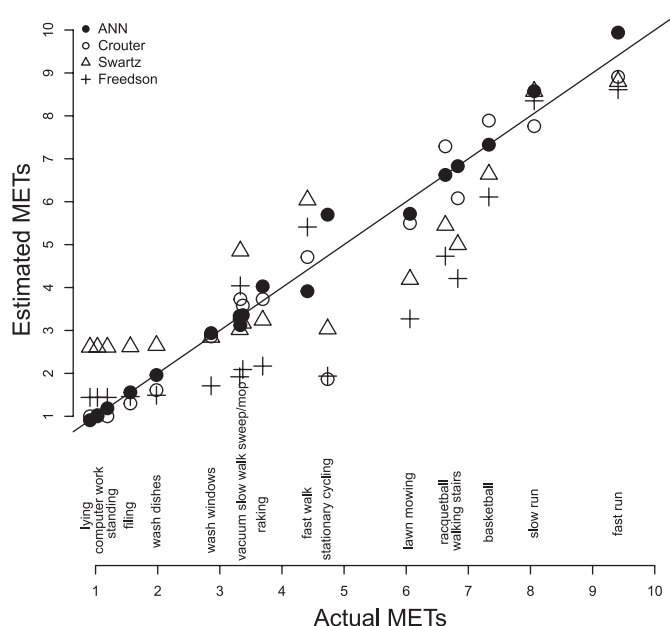


Fig. 2. Measured and estimated metabolic equivalents (METs) for each activity using two regressions equations, the two-regression method of Crouter et al. (9) and an artificial neural network (ANN). Cross-validation group from Crouter et al. (9) is used.

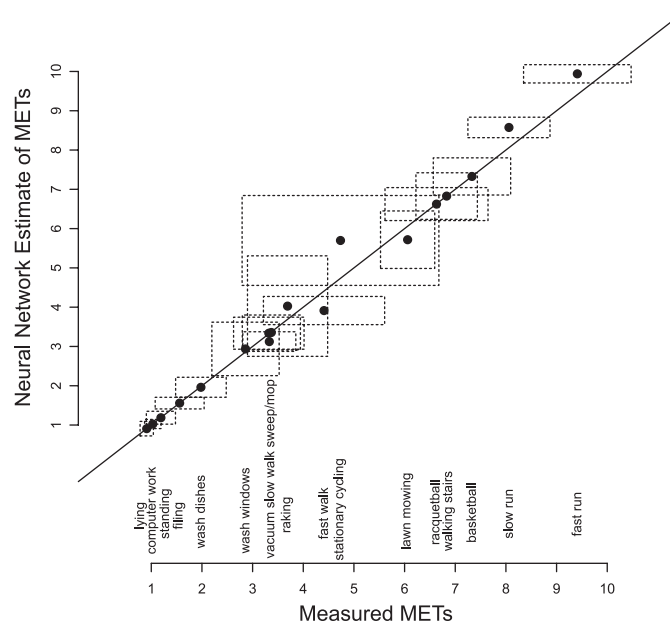


Fig. 3. Measured and ANN estimated METs for each activity with SDs. Cross-validation group from Crouter et al. (9) is used.

shows the activity-to-activity variability of the cross-validated root mean squared error.

For the PA-type application, the test statistic is the fraction of minutes for which the ANN's prediction of activity type matched the activity type the person was recorded to be doing. In total, the leave-one-subject-out cross-validated estimate of this statistic is 88.8% (95% CI: 86.4–91.2%). Figure 4, *bottom*, shows the subject-to-subject variability of cross-validated estimates of estimation accuracy, and Fig. 5, *bottom*, shows the activity-to-activity variability of cross-validated estimates of estimation accuracy. Table 5 contains a confusion matrix that illustrates the frequency with which one activity type was confused with another.

DISCUSSION

We have implemented a statistical methodology that estimates METs and activity type from the data produced by a single “off-the-shelf” hip-mounted uniaxial accelerometer (Actigraph 7164). Table 4 compares our estimates of METs to two cut-point methods (10, 20) and the method developed by Crouter and Bassett (6). We compare the methods using three statistical tools: bias, standard error, and root mean squared error. We make these comparisons in two ways: using each minute's predictions and using the average prediction for each

activity, both with and without cycling. Note that the variability is smaller when the statistics are computed for each activity, since the averaging step reduces the minute-to-minute variability of the data. The table suggests that our method offers improved estimates of METs. Additionally, the neural network approach also allows one to estimate activity type, which simpler regression-type methodologies do not.

The minute-by-minute standard errors have practical implications about the precision of these methods when used to estimate MET·h in a free-living population. For instance, suppose an accelerometer is worn for 12 h, and MET·h are of interest. The standard error of the neural network's estimate of MET·h is $\sqrt{(12)(1.22)/\sqrt{(60)}} = 0.55$ MET·h and the standard error for the method of Crouter and Bassett (6) is $\sqrt{(12)(1.69)/\sqrt{(60)}} = 0.75$ MET·h. As a result, the respective 95% CIs have widths of 2.14 MET·h = $(2)(1.96)\sqrt{(12)(1.22)/\sqrt{(60)}}$ and 2.95 MET·h = $(2)(1.96)\sqrt{(12)(1.69)/\sqrt{(60)}}$. The more flexible analytic technique results in a CI that is 28% narrower. These calculations do not consider bias, since neither method was statistically significantly biased. Additionally, this example assumes that the subject engaged in approximately the same types of activities as were done in the present study. As is suggested by the relative sizes of the boxes in Fig. 3, if an individual engaged in mostly low-MET activities, the estimate of MET·h would be more precise, and the estimated MET·h

Table 4. Performance summaries for ANN and regression methods

	By Activity, No Cycling			By Activity, With Cycling			By Minute, No Cycling			By Minute, With Cycling		
	Bias	SE	rMSE	Bias	SE	rMSE	Bias	SE	rMSE	Bias	SE	rMSE
Neural network	−0.10*	0.42	0.43	−0.07*	0.75	0.75	−0.02*	1.15	1.15	0.05*	1.22	1.22
Crouter et al. (9) two regressions	0.10*	0.72	0.73	−0.26*	1.22	1.25	−0.36*	1.35	1.40	−0.50*	1.53	1.61
Swartz et al. (20) regression	−0.14*	1.38	1.39	−0.31*	1.50	1.53	−0.15*	1.63	1.64	−0.30*	1.74	1.77
Freedson et al. (10) regression	−1.04	1.24	1.62	−1.21	1.41	1.86	−1.04	1.57	1.88	−1.21	1.70	2.09

Values are in metabolic equivalents. rMSE, root mean square error. *Not statistically significantly different from zero at $\alpha = 0.05$.

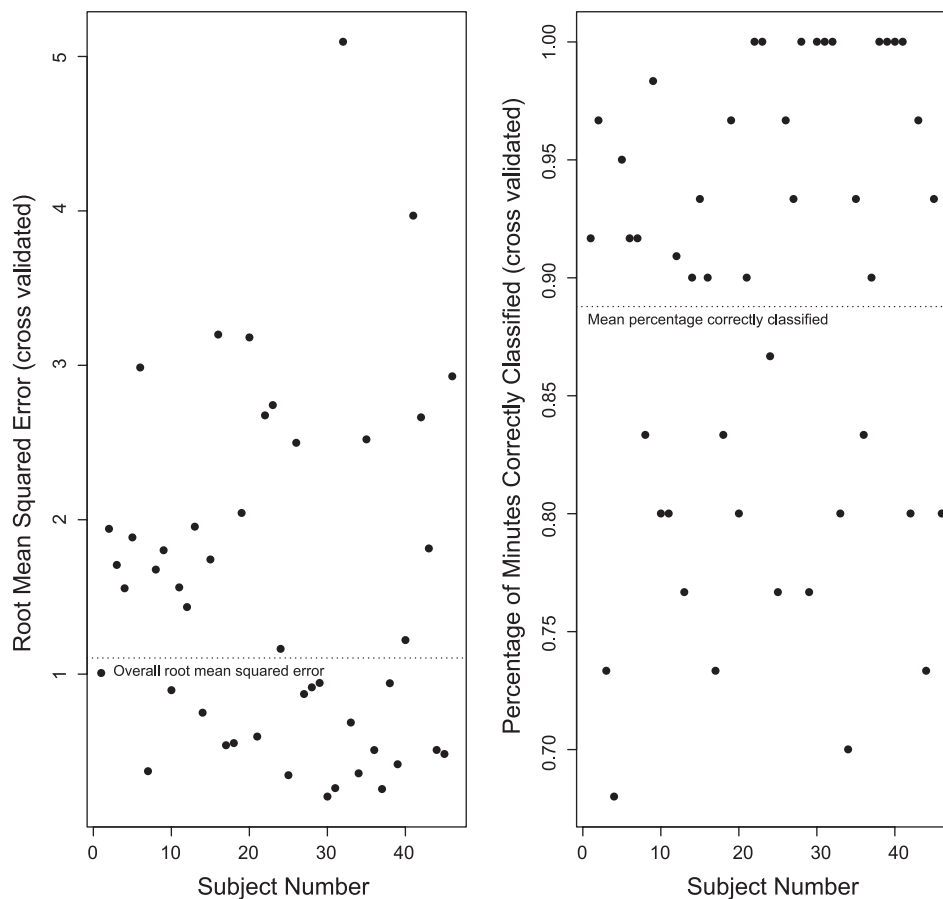


Fig. 4. Performances of the MET and activity type ANNs when the model is trained on all subjects but one. The plotted points (●) evaluate the predictions for the left-out subjects. The unit for root mean squared error is METs.

for an individual who engaged in mostly higher MET activities would have a wider 95% CI.

Other investigations have successfully employed various types of pattern recognition methods to identify activity type. Applying a Bayes Classifier method and HMMs to a three-dimensional accelerometer mounted in a glove, Chang et al. (5) correctly identified 90% of nine different free-weight exercises and correctly counted repetitions of each exercise 95% of the time. Lester and colleagues (14, 15) reported a similar rate of activity type identification from a three-dimensional accelerometer worn at any one of three locations using static classifiers coupled with a temporally smoothing HMM to estimate activity type.

To estimate energy expenditure, Rothney et al. (19) used the raw signal from a biaxial accelerometer in a 10-feature ANN with one hidden layer. The mean difference between ANN-estimated total energy expenditure and total energy expenditure directly measured was 21 kcal/day. We applied a similar ANN technique to the second-by-second time-integrated accelerometer signal and estimated the energy expenditure of specific activities, which may be more useful in free-living applications of pattern recognition methodologies.

Our methodology has several limitations. One is that we developed and tested it on 48 subjects doing 18 activities. Validation of these methods on more people doing more activities and free-living subjects is an important next step.

A second limitation is that we estimated both PAEE and activity type on a minute-to-minute basis, and human activity can take place on a different time scale. Additionally, we were

somewhat unsuccessful in reliably and accurately identifying the actual activity mode. There are several possible reasons for this. One possible reason is that the activities were “self-paced,” and there were individual variations in locomotion pace and the way other activities were performed. We chose to use “self-pacing” to simulate the free-living environment, where not everyone locomotes at the same speed.

A second possible reason for our lack of activity classification success is that we used an approach where a single model is applied to all subjects. This is in contrast to an approach where a separate model is created for each subject. Others have demonstrated that multiple accelerometers and subject-specific models can accurately and reliably identify specific activities (14, 21). We surmise that subject-specific models might be relatively successful to identify actual activities from uniaxial accelerometers as well. While it is tempting to propose that including subject-specific data, such as height, weight, sex, or age as covariates (additional x_p values), in the model might improve model performance, we did not find that to be the case.

The approach of using a single hip-mounted uniaxial accelerometer also has the inherent limitation that different activities can produce very similar accelerometer signals. For instance, data in Table 3 suggest that slow running and fast running produce very similar distributions of accelerometer counts. Figure 2 shows that this results in similar estimates of METs for both activities, even though their actual METs differ. Figure 2 also shows that the method does not completely fail for stationary cycling, an activity that does not include a lot of body movement, but has a relatively high MET value.

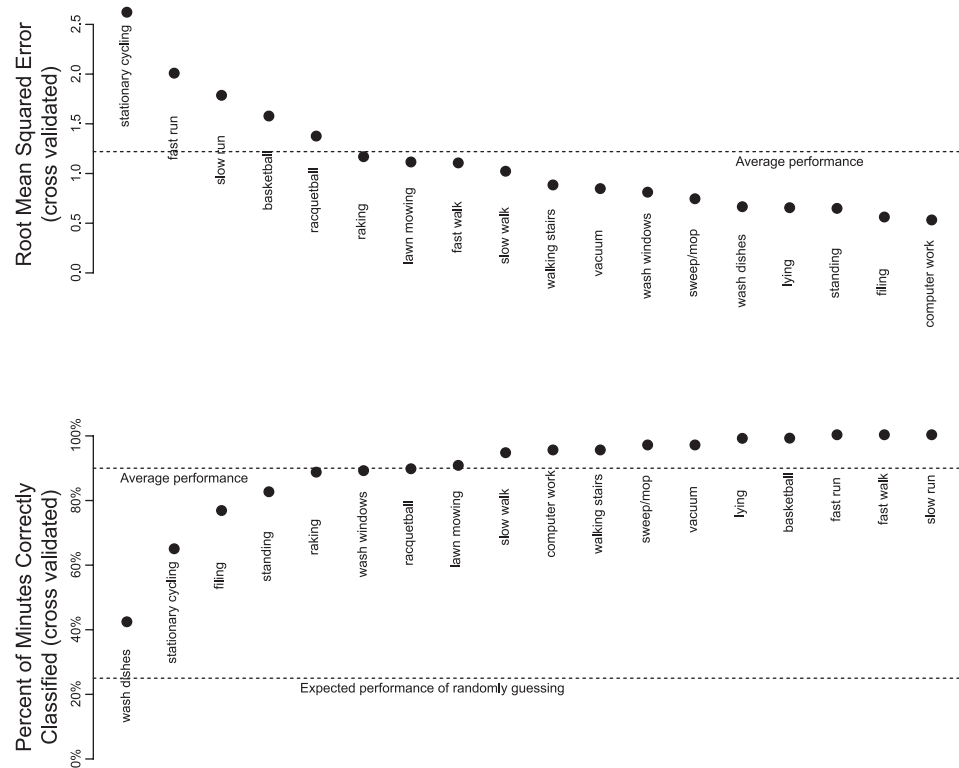


Fig. 5. Activity type classification accuracy and MET estimation by activity. The unit for root mean squared error is METs.

Our implementation of neural networks had some empirical success, and neural networks in the nnet package are relatively easy to use. Different (and perhaps more expensive) neural network software could have more success, and our choice of inputs was driven by practical success, and an infinite number of other choices are possible. Some may lead to improved performance. We found that removing any one of the five percentiles as predictors nominally worsened performance, but we did not test all 32 subsets of those 5 predictors. Equally spacing the percentiles (17th, 33rd, 50th, 67th, 83rd percentiles) worsened performance by <1%. Additionally, neural networks are one of many “nonparametric” regression and pattern recognition methodologies that could be applied to this problem. Other choices include support vector machines, multivariate adaptive regression splines, and tree methodologies. A recent book-length review can be found in Ref. 11. This is an active and evolving subfield of statistics and computer science, and other methods may lead to improved performance. Some of these more sophisticated statistical techniques also might be able to take advantage of additional information that might be in “three-axis” accelerometers and raw accelerometer sig-

nals, as opposed to the 1-s filtered single-axis counts we used. Use of the raw acceleration signals has the potential to help with individual activity identification. More sensitive summaries of the temporal dynamics of the accelerometer data, such as spectral methods, might be useful when raw accelerometer signals are used, but we did not find that to be the case when using second-by-second data.

Conceptually, our method may be used in the same way that “cut point models” have been used. Other researchers who have collected second-by-second Actigraph accelerometer data can apply our trained model (a piece of “open source” software that is available from the authors or code in the APPENDIX to this paper) to their accelerometer data. This will yield estimates of METs for their subjects that are more valid than those produced by previous methodology, and it will provide estimates of the amounts of time subjects spent doing the types of activities that we have defined. An open source “point-and-click” piece of software that implements these methods is possible and desirable, but that is beyond the scope of the current project. It also should be noted that we would expect the model’s performance to degrade if it were applied to subjects who were doing very different activities from those in Crouter et al. (6–9).

In summary, this study demonstrates the successful implementation of an ANN to estimate PAEE and general categories of activity type using a single uniaxial Actigraph accelerometer secured to the hip. The error in estimating PAEE is less than reported by others using the traditional regression approach. This improved performance likely is attributable to two factors: first, the ANN method is inherently more flexible than an approach that assumes a static parametric (e.g., linear model or known family of nonlinear functions with a small number of parameters) relationship between the inputs and the response.

Table 5. Confusion matrix to summarize activity-type classification performance

Actual Activity Type	Neural Net Classification of Activity Type			
	Low Level of Activity	Household Activity/Other	Locomotion	Vigorous Sport
Low level of activity	303	38	0	0
Household activity/other	88	443	19	5
Locomotion	0	15	513	2
Vigorous sport	0	8	3	179

Values are in minutes.

That is, the ANN uses the data to learn the “shape” of the relationship between the inputs and the output instead of assuming that the regression shape belongs to a relatively simple set of shapes. The second reason for the improved performance of the ANN method is that the inputs use more of the information in the accelerometer signals than just the minute-by-minute means that are used by cut-point methods (10, 20) or the coefficient of variation and the mean used by Crouter and Bassett (6). These two factors are separate, and each might lead to improved performance on its own, but they also work together. Thus a flexible model that takes advantage of the richness of information in accelerometer signals seems to lead to improved performance.

APPENDIX: R CODE

ANN to Estimate METs

First, a data set must be created that has one row for each minute. Each row should contain METs for that minute and each of the six independent variables: the 10th, 25th, 50th, 75th, and 90th percentiles of the counts in the minute and the lag one autocorrelation. Three example rows of data follow:

METs	X10.	X25.	X50.	X75.	X90.	acf
3.39	1	4.75	12.5	23.25	54.1	0.3684387
3.39	1	5.75	14.0	40.25	62.6	0.6574136
3.39	2	5.00	11.0	21.25	44.7	0.1468472

After loading the neural network library, the command to fit the regression is

```
reg.nn ← nnet (METs ≈ ., data = training.data, size = 25,
rang = 1, skip = T, decay = 0.2666667, maxit = 50000, linout = T)
```

Prediction of METs for a new subject can be achieved with

```
predict (reg.nn, test.reg)
```

where test.reg is a data set like the one above, but without the METs column.

ANN to Estimate Activity Type

A data set similar to the one above needs to be prepared. Instead of the METs column though, it has an activity type column, i.e.

act.type	X10.	X25.	X50.	X75.	X90.	acf
locomotion	1	4.75	12.5	23.25	54.1	0.3684387
locomotion	1	5.75	14.0	40.25	62.6	0.6574136
locomotion	2	5.00	11.0	21.25	44.7	0.1468472

The command to fit in this case is:

```
class.nn ← nnet (act.type ≈ ., data = training.data, size = 25,
rang = 1, skip = T, decay = 0.06, maxit = 5000)
```

Prediction of activity type for a new subject can be achieved with

```
predict (class.nn, test.class)
```

where test.class is a data set like the one above, but without the activity type column.

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