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Utility of the Actiheart Accelerometer for Estimating Exercise Energy Expenditure in Female Adolescent Runners

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There is a growing need to accurately assess exercise energy expenditure (EEE) in athletic populations that may be at risk for health disorders because of an imbalance between energy intake and energy expenditure. The Actiheart combines heart rate and uniaxial accelerometry to estimate energy expenditure above rest. The authors' purpose was to determine the utility of the Actiheart for predicting EEE in female adolescent runners ($N = 39$, age 15.7 ± 1.1 yr). EEE was measured by indirect calorimetry and predicted by the Actiheart during three 8-min stages of treadmill running at individualized velocities corresponding to each runner's training, including recovery, tempo, and 5-km-race pace. Repeated-measures ANOVA with Bonferroni post hoc comparisons across the 3 running stages indicated that the Actiheart was sensitive to changes in intensity ($p < .01$), but accelerometer output tended to plateau at race pace. Pairwise comparisons of the mean difference between Actiheart- and criterion-measured EEE yielded values of 0.0436, 0.0539, and 0.0753 $\text{kcal} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ during recovery, tempo, and race pace, respectively ($p < .0001$). Bland–Altman plots indicated that the Actiheart consistently underestimated EEE except in 1 runner's recovery bout. A linear mixed-model regression analysis with height as a covariate provided an improved EEE prediction model, with the overall standard error of the estimate for the 3 speeds reduced to 0.0101 $\text{kcal} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. Using the manufacturer's equation that combines heart rate and uniaxial motion, the Actiheart may have limited use in accurately assessing EEE, and therefore energy availability, in young, female competitive runners.

Keywords*:* accelerometry, physical activity assessment, oxygen consumption, athletes

The literature is replete with studies of objective measures of physical activity in children and adolescents. In the past decade there have been over 50 published studies and review articles on the measurement of child and adolescent physical activity by accelerometry. Of these, nine validated various commercially available accelerometers using indirect calorimetry as the criterion measure of energy expenditure (Catellier et al., 2005; Corder et al., 2007; Ekelund, Yngve, Brage, Westerterp, & Sjostrom, 2004; Evenson, Catellier, Gill, Ondrak, & McMurray, 2008; Pate, Almeida, McIver, Pfeiffer, & Dowda, 2006; Puyau, Adolph, Vohra, & Butte, 2002; Schmitz et al., 2005; Stone, Esliger, & Tremblay, 2007; Treuth et al., 2004). Most published literature on accelerometry has been driven by the need to accurately assess volume and intensity of spontaneous physical activity to determine its role in obesity prevention (Corder et al., 2007; Freedson, Pober, & Janz, 2005; Pate et al., 2006; Treuth et al., 2004) and to evaluate whether children and adults are meeting the U.S. guidelines for moderate to vigorous physical activity (Pate et al., 1995). Recently, there has been an emerging need to accurately determine energy expenditure in athletic populations that may be at risk for health disorders related to an imbalance between energy intake and energy expenditure. Several well-controlled laboratory studies in young adult women have shown associations between low energy availability, defined as the amount of energy remaining for all body functions after subtracting exercise energy expenditure (EEE; Nattiv et al., 2007), and potentially serious health disorders including menstrual dysfunction, abnormal bone turnover, and low bone-mineral density (De Souza & Williams, 2004, 2005; Ihle & Loucks, 2004; Loucks, 2003; Loucks & Thuma, 2003). To determine energy availability, accurate measures of dietary energy intake and EEE are required. Assessment of energy availability is important, because low energy availability appears to be the underlying cause of menstrual dysfunction and low bone mass in some female athletes (De Souza & Williams, 2005; Hoch et al., 2009; Loucks & Thuma, 2003; Zanker & Swaine, 1998).

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To determine EEE in a field setting, objective, accurate, reliable, and unobtrusive measures are needed. The Actiheart accelerometer may show promise for assessing EEE in athletes, particularly in runners. Because the Actiheart combines heart rate (HR) and motion (accelerations) in the vertical plane, it may yield more accurate determination of EEE than either HR or motion alone (Brage, Brage, Franks, Ekelund, & Wareham, 2005; Corder, Brage, Wareham, & Ekelund, 2005; Crouter, Churilla, & Bassett, 2008; Fudge et al., 2007). To our knowledge, only one study has validated the Actiheart using indirect calorimetry during treadmill running in children (Corder et al., 2005). Those investigators reported a strong association between predicted and measured EEE ($R^2 = .86$) and a mean difference of only 10 $J \cdot kg^{-1} \cdot min^{-1}$ (0.00239 $kcal \cdot kg^{-1} \cdot min^{-1}$). However, the subjects in that study were not competitive runners, and the treadmill velocity did not exceed 12.2 km/hr (Corder et al., 2005). This is important to note, because uniaxial accelerometer data alone have been shown to plateau at faster speeds (Brage, Wedderkopp, Franks, Andersen, & Froberg, 2003; Nichols, Morgan, Chabot, Sallis, & Calfas, 2000). We hypothesized that the algorithm developed by the Actiheart manufacturer using combined HR and accelerometry would yield accurate estimates of EEE in young competitive runners. Thus, the current study was designed to compare EEE determined by the Actiheart device to that determined from indirect calorimetry during treadmill running at velocities that mimicked each athlete's pace during recovery/easy, tempo/moderate, and race/vigorous training. Our overall goal was to determine the utility of the Actiheart for assessing the EEE equation component for determining energy availability in adolescent female runners.

Subjects and Methods

Subjects

Forty-one female distance runners participating on interscholastic teams from four high schools in southern California during the 2008 cross-country season were recruited to participate in the study. To be included in the study, a runner had to be 14–18 years old, be currently participating on the school's cross-country team, have competed in a minimum of 1 year of cross-country training and racing, and be willing to participate in all study measures. Because the aim of the main study in which the runners were asked to participate was to assess bone turnover/bone mass, menstrual function, and energy availability, runners were excluded if they reported any disease or medical condition or were taking any medication known to interfere with bone metabolism. This study was approved by the San Diego State University and the University of California, Davis institutional review boards. The main study was registered with the National Institutes of Health Clinical Trials (NCT01059968).

Measures

On the morning of the eighth day after this 7-day observational study, after an overnight fast, the runners reported to the laboratory, where they underwent a blood draw and other measures (as part of the main study) and a treadmill running test composed of three 8-min bouts of running. Because participants arrived at the laboratory in a fasted state, immediately after the blood draw and approximately 30 min before their run test they consumed approximately 100 kcal from either an energy bar or yogurt and drank approximately 250 ml of water to help prevent a possible hypoglycemic response and ensure normal hydration.

Treadmill Testing. The treadmill velocity for each bout of running was determined from each girl's current 1-mile personal-best track time as verified by her coach. The velocity at each stage was calculated as follows: Stage 1 = recovery/easy pace: calculated as the velocity (miles/hr) equal to the runner's 1-mile time plus 3 min and 15 s); Stage 2 = tempo/moderate pace: 1-mile time plus 2 min and 15 s; Stage 3 = race/vigorous pace: 1-mile time plus 1 min and 15 s The treadmill was maintained at a grade of 1% throughout the test. All runners warmed up for 2 min (the first minute at 2 miles/hr, the second at 3 miles/hr). The speed was then increased to the runner's recovery pace to begin the first 8-min bout. Between stages, runners walked for 1 minute at 2 miles/hr. The order of the three 8-min bouts was not randomized to avoid a residual effect of elevated HR and energy expenditure, had the more intense bout occurred first.

Expired air was collected continuously throughout the treadmill session. Oxygen uptake (VO_2) was assessed by indirect calorimetry using a Truemax metabolic cart (ParvoMedics Inc., Sandy, UT). VO_2 data (L/min) for each of the three bouts of exercise were converted to energy expenditure ($kcal \cdot kg^{-1} \cdot min^{-1}$) by multiplying the mean value of Minutes 4–7 by its respective mean caloric equivalent determined by the corresponding respiratory-exchange-ratio value, then dividing that value (kcal/min) by body weight. To determine net energy expenditure, resting energy expenditure (estimated from the equation used by the Actiheart manufacturer; Harris & Benedict, 1918) was calculated for each girl and then subtracted from total energy expenditure determined by indirect calorimetry. This criterion-measured value of EEE in kcal $\cdot kg^{-1} \cdot min^{-1}$ above rest was then compared with EEE measured by the Actiheart during the same time frame.

Accelerometer Procedures. Participants wore an Actiheart accelerometer (Respironics Co., Bend, OR, software version 2.0) during the treadmill test. This device measures accelerations, recorded as counts, and HR independently and can also integrate counts and HR to yield estimates of energy expenditure above resting energy expenditure. Proprietary algorithms compute net energy expenditure by estimating resting energy expenditure from standard equations (Harris & Benedict, 1918) and subtracting resting energy expenditure from total energy expenditure. As a motion sensor, the Actiheart is a uniaxial accelerometer that detects vertical acceleration in the longitudinal axis of the trunk. The device weighs approximately 8 g and attaches unobtrusively to an individual's chest using two electrodes (Blue Sensor L, Ambu Co., Glen Burnie, MD). The Actiheart can be worn for up to approximately 11 days when set to epochs of 15 s, then downloaded. Runners wore the device on the left side of their chest, according to the manufacturer's instructions. Briefly, one electrode was placed just to the left of the sternum at approximately the second intercostal space, and the other was placed horizontally at the anterior axillary line. Because of the small size of most of our runners' chests, the wire connection between electrodes could not be straightened according to the manufacturer's instructions. Consequently, the Actiheart was taped to the chest in a looped fashion, with care taken to avoid crimping the wires. For comparison of HR values, the runners also wore a Polar HR monitor.

Anthropometric Measures. Before the treadmill protocol, height (stadiometer) and weight (digital scale), without shoes, were measured by a research assistant and recorded to the nearest 0.5 cm and 0.1 kg, respectively. Body composition, including fat mass (g), percent body fat, and lean-tissue mass (g), was assessed by DXA on a Prodigy Advance densitometer (GE/Lunar, Madison, WI, Software version 10.10). The coefficient of variation for fat and lean-tissue mass measured in our laboratory twice on 30 subjects is less than 1.5%.

Statistical Analyses

Analyses were conducted using SPSS version 17.0 and SAS version 9.2. Means and standard deviations were used to describe characteristics of the study sample. Validity and reliability (internal consistency) of the Actiheart were determined from three 8-min bouts of treadmill running at moderate, hard, and very hard intensities. Data for Minutes 4–7 of each stage were included in all analyses. Minutes 1–3 were excluded to ensure that data points included only those at steady state. Minute 8 was excluded to eliminate the possibility of any upward drift in HR toward the end of a bout, particularly at race pace. Repeated-measures ANOVA with Bonferroni post hoc tests was used to determine the sensitivity of the Actiheart to changes in running velocity. Paired *t* tests were used to compare EEE measured by the Actiheart with that measured by the criterion of indirect calorimetry. Adjusted Bland–Altman plots were constructed to show the limits of agreement of the two methods of determining EEE (Bland & Altman, 1986). The difference between criterion-measured and Actiheart-measured EEE was plotted against the criterion method, because the criterion method is considered the gold standard for determining EE. The 95% limits of agreement represent the mean difference (criterion minus Actiheart) ± 1.96 *SD* of the differences.

Prediction of EEE from Actiheart-measured EEE was determined using a linear mixed-model regression analysis. Because multiple measurements were taken on each subject, the mixed-model regression analysis accounted for correlations among measurements made on the same subject. Height in centimeters and percent body fat were tested for inclusion as covariates. Height was included partially to account for differences in stride length that may affect the association between energy expenditure and activity counts as measured by the Actiheart. Model selection was conducted using a forward stepwise approach that involved the comparison of Akaike information criterion (Akaike, 1974) values across a variety of univariate and multivariate models. Preference was given to lower values of Akaike information criterion. To assess quality of fit, plots comparing predicted and observed values were prepared and the standard error of the estimate (*SEE*) was calculated.

Results

The physical characteristics of participants are shown in Table 1. Data from 2 subjects were excluded from all analyses because of apparent malfunction of the HR function of the Actiheart during Stages 2 and 3 of treadmill testing. This may have been caused by poor electrode adherence as a result of sweating. Thus, the final sample size for analysis was $N = 39$. For 3 additional subjects who had obviously erroneous HR values at only one of the three treadmill stages, EEE at that stage was imputed from the individual regression line for HR–EEE extrapolated to age-predicted maximum HR. In these three cases, the HR value from the Polar heart watch was substituted for the missing value from the Actiheart.

As a group, the runners were within a healthy range for weight and body-mass index (BMI). However, there was a wide range of BMI (14–25) and percent body fat (12–33%), with 7 of the 39 girls below the 10th percentile for BMI for their age (Centers for Disease Control and Prevention, 2010).

Table 1 Participants' Physical Characteristics (*N* = 39)

	***M* (*SD*)**	**Range**
Age (years)	15.7 (1.1)	14.0–17.0
Height (cm)	164.3 (5.8)	152.8–175.5
Weight (kg)	54.1 (8.0)	34.1–68.0
Body-mass index (weight/m^2)	20.0 (2.6)	14.6–25.6
Body fat (%)	22.2 (6.4)	12.2–33.1
REE[a] (kcal/day)	1,402 (80)	1,198–1,527

[a] Resting energy expenditure, predicted from Harris–Benedict equation (Harris & Benedict, 1918).

Reliability data measured by the Actiheart across Minutes 4–7 of each stage are presented in Table 2. Intraclass correlation coefficients (*ICC*s) for HR (.792–.884) and EEE (.775–.875) indicated moderately high internal consistency of the device. Bivariate correlations between HR measured by the Actiheart and Polar heart watch yielded correlation coefficients of $r = .912$, .935, and .953 for Stages 1, 2, and 3, respectively, indicating very strong agreement between devices.

Repeated-measures ANOVA of HR and EEE across the three stages of treadmill running is reported in Table 3. The Actiheart significantly detected changes in HR and EEE across the three running intensities. Post hoc pairwise comparisons indicated significant differences between all stages ($p < .01$).

Table 2 Reliability (Internal Consistency) of the Actiheart for Heart Rate and Exercise Energy Expenditure (EEE) Above Resting Energy Expenditure During Treadmill Exercise

Variable	Stage 1	Stage 2	Stage
Heart rate	.884	.817	.792
EEE	.875	.775	.784

Note. Stage 1 = recovery/easy pace (calculated as the velocity [miles/hr] equal to the runner's 1-mile time plus 3 min and 15 s); Stage 2 = tempo/moderate pace (1-mile time plus 2 min and 15 s); Stage 3 = race/vigorous pace (1-mile time plus 1 min and 15 s). Values are intraclass correlation coefficients for Minutes 4–7 of each stage.

Comparisons between criterion- and Actiheart-measured EEE for Minutes 4–7 of each treadmill stage are shown in Table 4. Significant differences in mean EEE between the criterion and Actiheart measures were detected for each stage of exercise ($p < .001$). The mean difference ranged from 0.0436 kcal · kg^{-1} · min^{-1} at recovery pace to 0.0753 kcal · kg^{-1} · min^{-1} at race pace.

Figure 1 illustrates Actiheart-measured EEE plotted against EEE measured by the criterion, with a diagonal reference line indicating perfect agreement. The Actiheart consistently underestimated EEE for all runners with the exception of 1 during her recovery bout. Figure 2 shows the adjusted Bland–Altman plot of the difference between criterion-measured and Actiheart-measured EEE plotted against the criterion measure of indirect calorimetry. The plot indicates a trend of increasing differences between EEE measurements associated with increasing magnitude of criterion-measured EEE. Differences between criterion-measured and Actiheart-measured EEE were positively correlated with values of criterion-measured EEE ($r = .8290$, $p < .0001$). Moreover, the limits of agreement indicated that EEE was underestimated by at least 1.96 *SD*s of the mean difference in 4 subjects at race pace.

Table 3 Sensitivity of the Actiheart in Detecting Change in Exercise Intensity During Treadmill Exercise

	Stage 1	Stage 2	Stage 3	Pairwise contrasts[a]
Heart rate (beats/min)	162 (14)	177 (14)	189 (12)	S3 > S2 > S1, $p < .01$
Exercise energy expenditure[b] (kcal · kg^{-1} . min^{-1})	0.120 (0.015)	0.138 (0.012)	0.154 (0.013)	S3 > S2 > S1, $p < .01$

Note. Stage 1 = recovery/easy pace (calculated as the velocity [miles/hr] equal to the runner's 1-mile time plus 3 min and 15 s); Stage 2 = tempo/moderate pace (1-mile time plus 2 min and 15 s); Stage 3 = race/vigorous pace (1-mile time plus 1 min and 15 s). Values are *M* (*SD*) of Minutes 4–7 of each stage.

[a] Repeated-measures ANOVA with Bonferroni post hoc tests. [b] Above resting energy expenditure (Harris & Benedict, 1918).

Table 4 Comparison of Exercise Energy Expenditure (EEE) Measured by the Criterion (Indirect Calorimetry) With Actiheart-Measured EEE

Stage	Measure	*M* (*SD*)	Mean difference	95% CI
1	Criterion	0.1640 (0.0208)	0.0436	.0366–.0505*
	Actiheart	0.1200 (0.0149)		
2	Criterion	0.1934 (0.0192)	0.0539	.0485–.0594*
	Actiheart	0.1385 (0.0123)		
3	Criterion	0.2292 (0.0221)	0.0753	.0680–.0827*
	Actiheart	0.1537 (0.0134)		

Note. Stage 1 = recovery/easy pace (calculated as the velocity [miles/hr] equal to the runner's 1-mile time plus 3 min and 15 s); Stage 2 = tempo/moderate pace (1-mile time plus 2 min and 15 s); Stage 3 = race/vigorous pace (1-mile time plus 1 min and 15 s). Values are kcal · kg^{-1} . min^{-1} above resting energy expenditure (Harris & Benedict, 1918).

*$p < .0001$ compared with criterion-measured EEE.

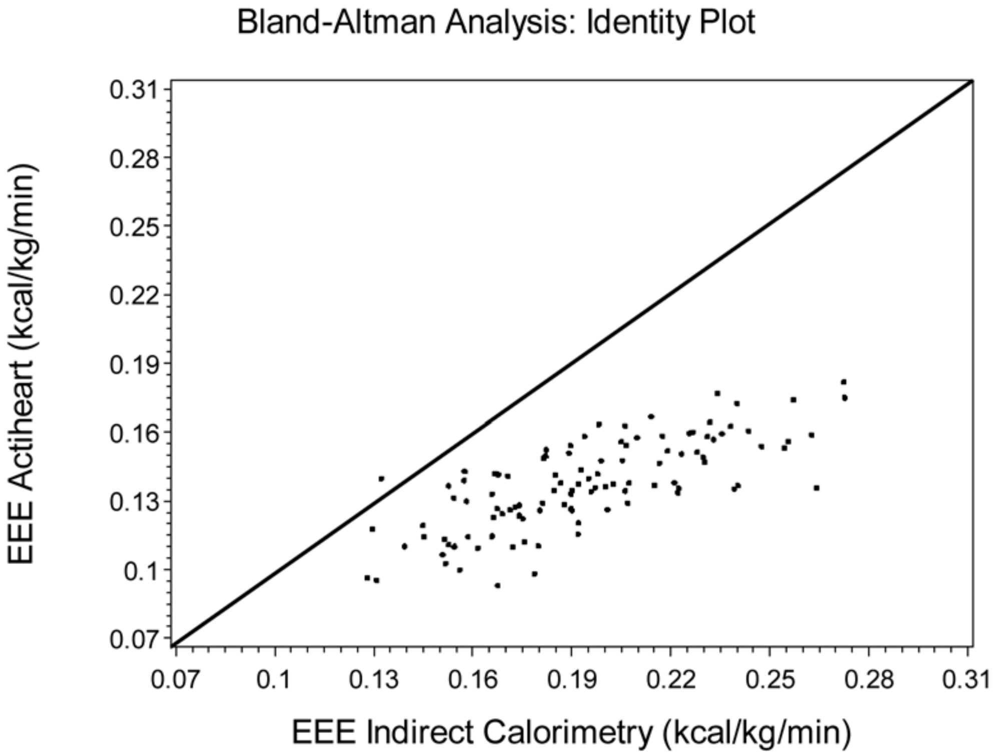

Figure 1 — Actiheart-measured exercise energy expenditure (EEE) plotted against criterion-measured EEE.

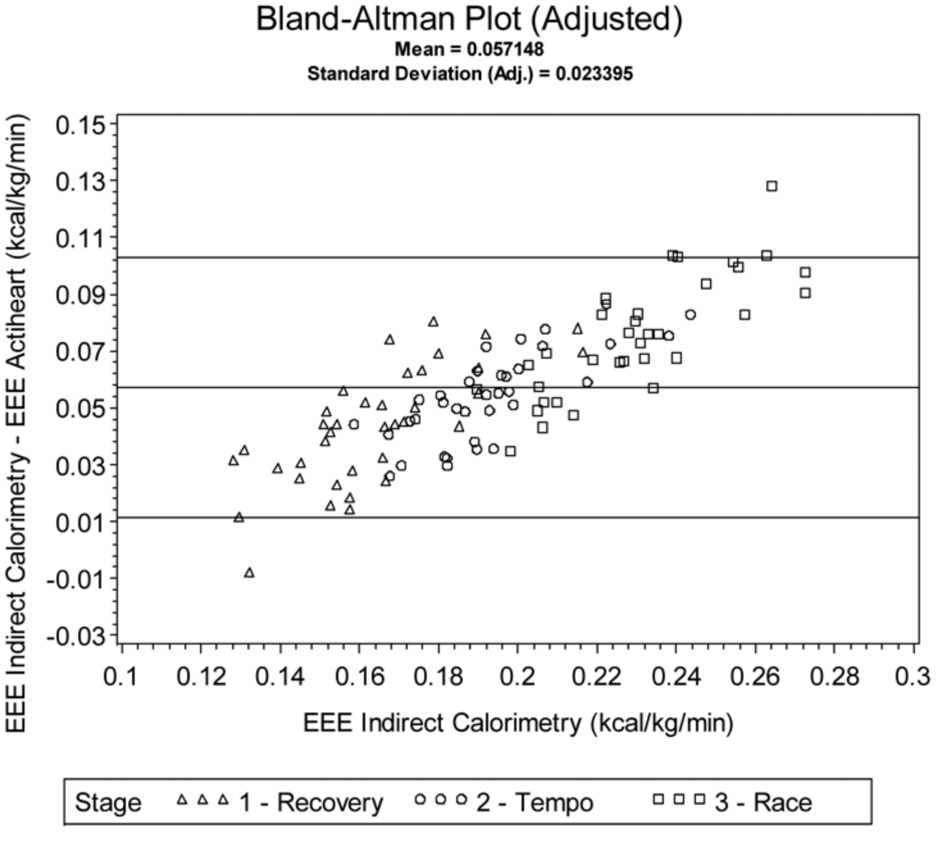

Figure 2 — The difference between criterion-measured exercise energy expenditure (EEE) and Actiheart-measured EEE plotted against criterion-measured EEE. Individuals in stages for which both EEE measurements were obtained are shown on the plot. Symbols serve to indicate the stage in which the EEE measurements were taken. Horizontal reference lines mark the mean difference and 1.96 *SD*s above and below it.

Table 5 Linear Mixed-Model Regression Analysis Fixed-Effect Estimates

	Estimate	Standard error	*t* (*df*)	*p*
Intercept	–0.1645	.09434	–1.74 (35)	.0900
Actiheart-measured exercise energy expenditure (kcal · kg^{-1} . min^{-1})	6.0862	.2829	21.52 (36)	<.0001
Height (cm)	0.00148	.00057	2.60 (33)	.0140

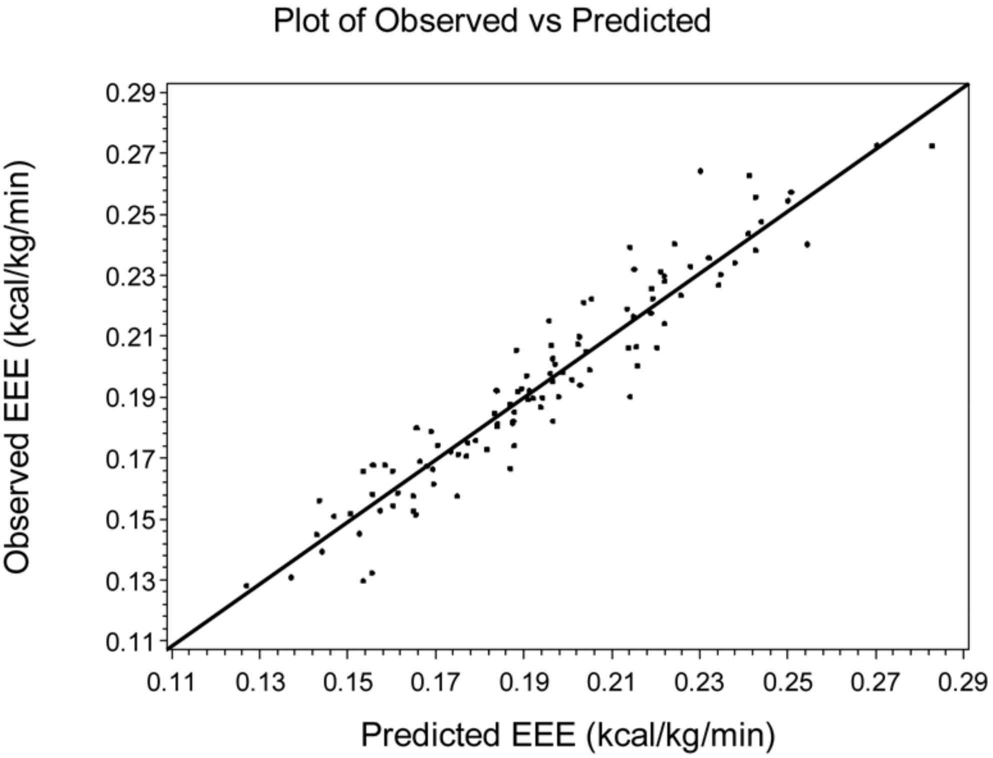

Figure 3 — Observed and predicted values plotted over a superimposed line with a slope of one and an intercept of zero. Observed values are criterion-measured exercise energy expenditure (EEE). Predicted values are those predicted by the linear mixed model including Actiheart-measured EEE squared and height.

The linear mixed-model regression analysis for the prediction of EEE resulted in inclusion of the squared value of Actiheart-measured EEE as a valid linear term and the inclusion of height as a significant covariate (Table 5). Random effects associated with the intercept and the squared value of Actiheart-measured EEE were included for each individual. The final model was fit using a variance components covariance structure. Model quality of fit is displayed in Figure 3, where observed and predicted values are plotted over a superimposed line with a slope of one and an intercept of zero. The *SEE* for the best-fit model was 0.01014 kcal · kg^{-1} · min^{-1}. Stage-specific *SEE*s were 0.011115, 0.00644, and 0.012052 kcal · kg^{-1} · min^{-1} for recovery, tempo, and race pace, respectively.

Discussion

Our results indicated that Actiheart output showed good reliability (internal consistency) for EEE and HR output at all three levels of exercise. Although it was not tested in the current study, others have reported very good interinstrument reliability of Actiheart devices (Brage et al., 2005). We also found high correlations in HR values between the Actiheart and Polar HR monitors.

The main finding of this study was that, using the manufacturer's equation that combined HR and accelerometer counts, the Actiheart consistently underestimated EEE during treadmill running in our sample of female high school distance runners. Furthermore, this underestimation became more pronounced as exercise intensity increased.

Previous studies of other uniaxial accelerometers (without HR capability) have shown a plateau in VO_2 at faster running speeds (Brage et al., 2005; Brage et al., 2003; Fudge et al., 2007). Fudge et al. reported a plateau in Actiheart counts at approximately 14–16 km/hr among young adult male distance runners. This range in speed approximated our runners' race pace (Stage 3). The failure of uniaxial accelerometers to detect faster speeds has been suggested to be caused largely by the lack of further increase in vertical motion in trained runners who have learned to increase their stride length and minimize wasted movement. This improvement in biomechanics and running economy in highly trained runners and the resultant minimization of vertical movement at faster speeds may explain the plateau effect that we and others (Fudge et al., 2007) observed at faster running velocity. Indeed, it has been shown that impulses from ground-reaction-force measures in the vertical plane were higher in less economical runners at a given speed (Heise & Martin, 2001). In our study, many girls were high-caliber runners. Eight (20%) were among the top 100 finishers in the California state championships, 5 were within the top 20, and 3 were within the top 10. Of the five teams participating in the study, two were ranked in the top 10 in the state.

The increasing error in prediction of EEE we observed as speed increased might also be a result of the Actiheart's inability to determine motion caused by increased horizontal forces that occur with increasing velocity. In addition to vertical motion, horizontal forces contribute greatly to energy expenditure in running (Chang & Kram, 1999). Because trained runners increase stride length as they increase speed more than inexperienced runners, it is plausible that because of its uniaxial design, the Actiheart lacks sensitivity in detecting faster speeds in trained runners who may minimize vertical forces, and therefore vertical motion, but maximize horizontal motion with increasing velocity.

Because of the known limitations in accurately detecting faster running speeds by accelerometer counts alone, we selected the Actiheart for its ability to combine HR and accelerometer output to assess EEE. Several studies have reported improved prediction of VO_2 or EEE when counts and HR were combined (Brage et al., 2005; Corder et al., 2005; Fudge et al., 2007; Moon & Butte, 1996). For example, Brage et al. (2005) reported very good accuracy of combined Actiheart counts and HR, with an R^2 value of .942 and *SEE* of 65.7 $J \cdot kg^{-1} \cdot min^{-1}$ (0.0157 $kcal \cdot kg^{-1} \cdot min^{-1}$) relative to VO_2 data collected during treadmill walking and running in adult men and women. In a sample of 12- to 13-year-old children, Corder et al. (2005) reported an R^2 of .86 and *SEE* of 69 $J \cdot kg^{-1} \cdot min^{-1}$ in their regression model, which included gender. However, the treadmill speeds tested in their studies were slower (8.5–12 km/hr) than the race pace in our study and below the speed at which others have observed a plateau in accelerometer output (Fudge et al., 2007). Furthermore, the participants in those two studies were not highly trained runners and therefore may have had greater vertical motion, and thus higher accelerometer counts at a given running speed, which might not be observed among trained runners with more optimal running economy (Heise & Martin, 2001).

Although the Actiheart was sensitive to changes in speeds ranging from recovery to race pace, as evidenced by the significant differences for all pairwise comparisons, the mean differences between EEE measured by indirect calorimetry and accelerometry were much larger than those reported recently in a field study that assessed EEE during a variety of activities, including slow and fast running, in young adult men and women (Crouter et al., 2008). For example, at a running velocity approximately equal to that of our subjects at tempo pace (~11.5 km/hr) those investigators reported a difference between the Actiheart and a portable indirect calorimeter of only 0.05 $J \cdot kg^{-1} \cdot min^{-1}$ (0.012 $kcal \cdot kg^{-1} \cdot min^{-1}$). Even when considering the large difference in mean body weight between their subjects and ours, the mean difference between predicted and measured absolute EEE (kcal/min) was still approximately 3 times larger than that in Crouter et al.'s study. The aforementioned biomechanical differences may explain part of this large difference between Crouter et al.'s and our study. In addition, differences in biomechanics associated with treadmill versus overland running could potentially yield differences in accelerometer counts at a given velocity (Elliott & Blanksby, 1976). Finally, our runners were assessed on a treadmill at a grade of 1% (which was selected to better approximate outdoor running as part of the main study), so it is also possible that EEE was partially underestimated because of insensitivity of the accelerometer to detect the small deviation in elevation from horizontal (Nichols et al., 2000). However, the increased VO_2 required to run at a 1% versus 0% grade would be only approximately 1–3 $ml \cdot kg^{-1} \cdot min^{-1}$ at the treadmill speeds we tested (American College of Sports Medicine, 2006). Even if the accelerometer were completely insensitive to the treadmill elevation, this error is very small.

To improve the predictability of EEE, we used a mixed regression model to adjust for factors thought to influence accelerometer output. The model with the best fit to predict EEE across all three stages involved the squared value of Actiheart-measured EEE and height. Height was entered into the equation as a proxy measure for stride length (Corder et al., 2005). The squared value of Actiheart-measured EEE accounted for the nonlinear nature of the relationship between Actiheart- and criterion-measured EEE. Through the use of a quadratic term, predicted EEE increases at a greater rate as the magnitude of Actiheart-measured EEE increases. The model predicted an increase in EEE of 0.00148 $kcal \cdot kg^{-1} \cdot min^{-1}$ for every additional centimeter of height, indicating that the Actiheart device may underestimate EEE to a greater extent in taller individuals and perhaps in runners with longer stride length.

The *SEE* of 0.01014 $kcal \cdot kg^{-1} \cdot min^{-1}$ suggests that the model provides a substantial improvement over the use of unadjusted Actiheart-measured EEE as a criterion measure. The stage-specific *SEE* values of 0.011115, 0.00644, and 0.012052 kcal · kg^{-1} · min^{-1} for recovery, tempo, and race pace, respectively, indicate that the model most accurately predicts EEE at tempo pace and is less accurate at recovery and race paces. Assuming that most training time is spent at tempo pace, the overall error in estimating EEE might be further reduced on a typical training day. In our proposed model, the average of the difference between observed EEE values, according to the criterion measure, and predicted EEE values is –1.97142E-17 kcal · kg^{-1} · min^{-1}. When comparing this average difference between criterion and predicted values for our proposed model with the average difference for the unadjusted Actiheart values (0.057148 kcal · kg^{-1} · min^{-1}), we can see that the proposed model almost entirely eliminates the measurement bias encountered when using unadjusted Actiheart-derived EEE values. Our proposed model becomes increasingly advantageous when summing EEE values across extended periods of time, when the cumulative difference could become very large. The small *SEE* and the minimal bias of the sum of repeated measurements make our proposed model a large improvement over the use of unadjusted Actiheart measurements in predicting EEE. Although a prediction model was constructed rather than a prediction equation, by modeling the correlations between measurements made on the same subject we were able to obtain improved fixed-effects estimates (Table 5) that can be used in an equation to predict EEE. The increased *SEE* at recovery and race paces indicates that additional consideration should be given before using the prediction model at these paces.

The improvement in the prediction of EEE using our model, in which height was a significant covariant, provides support for measuring and adjusting for stride length in future studies. Furthermore, a triaxial accelerometer, which assesses both horizontal and vertical motion, may improve the prediction of EEE in runners, because horizontal forces, which are an important determinant of the energy cost of running (Chang & Kram, 1999), would be captured.

Limitations of the Study

Two limitations of the study should be noted. First, as our adjusted model revealed, height was a significant covariate in the prediction of EEE. However, it would have been advantageous to have a direct measure of stride length as a predictor variable, rather than its surrogate measure of height. Second, independent validation of our prediction equation on a separate population of female adolescent runners would be valuable in assessing the model's true applicability in this specific population.

In conclusion, when using the manufacturer's equation that combines HR and uniaxial motion, the Actiheart may have limited use in assessing EEE, and therefore energy availability, in young, trained female runners, particularly at faster running speeds. Because the inclusion of subject height in our regression model greatly improved the prediction of EEE, we recommend that future studies consider biomechanical and other variables that may affect vertical or horizontal displacement, and therefore activity counts, when developing prediction equations for highly trained runners.

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