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<p>13. ABSTRACT (Maximum 200 words)</p> <p>Background: Walking and running are major physical activities that can play a significant role in reducing the likelihood of obesity and chronic diseases such as Type II diabetes. To assess the physical activity patterns, valid new methods are needed that to quantify the metabolic cost of locomotion (MLOCO) and daily total energy expenditure (TEE). Purpose: To compare field measurements of TEE estimated using foot-ground contact time (Tc) pedometry (TEEPEDO) with TEE measured by the criterion doubly labeled water (DLW) method (TEEDLW).</p> <p>Methods: Seven male US Marine test volunteers (<math>27 \pm 4</math> years of age [mean <math>\pm</math> SD]; weight = <math>83.4 \pm 11.5</math> Kg; height = <math>182.2 \pm 4.5</math> cm; body fat = <math>16.9 \pm 3.2</math> %; N = 7) participating in a field training exercise were studied over two days. Daily TEE was measured by DLW (TEEDLW) and by Tc-pedometry. TEEPEDO = (calculated resting energy expenditure + MLOCO), where MLOCO was derived from total weight (body weight + load weight) and pedometer measurements of Tc.</p> <p>Results: TEEDLW = <math>15.07 \pm 1.67</math> MJ.d-1 (mean <math>\pm</math> SD) and TEEPEDO = <math>15.11 \pm 0.93</math> MJ.d-1 (N = 7; anomalous TEE data from one subject was excluded from analysis). Mean bias (TEEPEDO - TEEDLW) was 0.04 MJ, and mean error (SD of difference between TEEPEDO and TEEDLW) was 1.70 MJ.</p> <p>Conclusions: These results suggest that valid estimates of the mean TEE of small groups of physically-active subjects can be obtained using Tc-pedometry.</p>			
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## Military Metabolic Monitoring

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# Total Energy Expenditure Estimated Using Foot-Ground Contact Pedometry

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### ABSTRACT

Routine walking and running, by increasing daily total energy expenditure (TEE), can play a significant role in reducing the likelihood of obesity. The objective of this field study was to compare TEE estimated using foot-ground contact time (Tc)-pedometry (TEE<sub>PEDO</sub>) with that measured by the criterion doubly labeled water (DLW) method. Eight male U.S. Marine test volunteers [27 ± 4 years of age (mean ± SD); weight = 83.2 ± 10.7 kg; height = 182.2 ± 4.5 cm; body fat = 17.0 ± 2.9%] engaged in a field training exercise were studied over 2 days. TEE<sub>PEDO</sub> was defined as (calculated resting energy expenditure + estimated thermic effect of food + metabolic cost of physical activity), where physical activity was estimated by Tc-pedometry. Tc-pedometry was used to differentiate inactivity, activity other than exercise (i.e., non-exercise activity thermogenesis, or NEAT), and the metabolic cost of locomotion (M<sub>LOCO</sub>), where M<sub>LOCO</sub> was derived from total weight (body weight + load weight) and accelerometric measurements of Tc. TEE<sub>PEDO</sub> data were compared with TEEs measured by the DLW (<sup>2</sup>H<sub>2</sub><sup>18</sup>O) method (TEE<sub>DLW</sub>): TEE<sub>DLW</sub> = 15.27 ± 1.65 MJ/day and TEE<sub>PEDO</sub> = 15.29 ± 0.83 MJ/day. Mean bias (i.e., TEE<sub>PEDO</sub> - TEE<sub>DLW</sub>) was 0.02 MJ, and mean error (SD of individual differences between TEE<sub>PEDO</sub> and TEE<sub>DLW</sub>) was 1.83 MJ. The Tc-pedometry method provided a valid estimate of the average TEE of a small group of physically active subjects where walking was the dominant activity.

### INTRODUCTION

**R**OUTINE AEROBIC EXERCISE, such as walking and running, can increase total energy expenditure (TEE), improve physical fitness, and reduce the likelihood of obesity, Type 2 diabetes, and other chronic disorders.<sup>1-3</sup> However,

the association of physical activity, metabolic energy expenditure, and health is not fully understood. For example, exercise does not always have a clear impact on the management of obesity.<sup>4</sup>

Ambulatory monitoring of free-living individuals is one way to improve our quantitative

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understanding of the role of physical activity and energy expenditure in health management.<sup>5-7</sup> New wearable monitors are needed that can unobtrusively and reliably gather data on the type, duration, frequency, intensity, and metabolic cost of physical activity.

A number of field methodologies exist to assess TEE. Standard field methods of assessing the metabolic cost of locomotion ( $M_{LOCO}$ ) include ambulatory indirect calorimetry,<sup>7</sup> and doubly labeled water (DLW).<sup>8,9</sup> Direct observation is valid,<sup>10</sup> but labor-intensive and difficult to scale to large groups of subjects. Ambulatory indirect calorimetry can measure minute-to-minute energy expenditure, but is obtrusive and requires the use of a mouthpiece or mask.<sup>7</sup> The DLW ( $^2H_2^{18}O$ ) method of measuring daily TEE is valid and unobtrusive, but expensive and typically only used over intervals of 2 or more days.<sup>11</sup>

Field methods of estimating the metabolic cost of physical activity include direct observation (factorial method),<sup>8</sup> heart rate (HR) monitoring,<sup>12</sup> accelerometry,<sup>5,13,14</sup> and pedometry.<sup>15-17</sup> The HR method is not valid for light physical activity and requires individual calibration to account for individual variation in HR-to- $VO_2$  relationship.<sup>12</sup> The output of waist-mounted accelerometers is correlated with the  $M_{LOCO}$  over level terrain, but not well correlated to the metabolic cost of non-locomotion activities.<sup>13,14</sup> Standard pedometry is objective, inexpensive, unobtrusive, and relatively reliable.<sup>16</sup> However, most pedometers only record total step count, do not provide data on the pattern or intensity of locomotion, and, as with accelerometry, provide only indirect estimates of  $M_{LOCO}$ .

The present study focuses on a unique type of pedometry that estimates  $M_{LOCO}$  from foot-ground contact time (Tc) measurements and total subject weight (body weight + load).<sup>17</sup> The rate of metabolic energy expenditure during walking or running is primarily determined by the cost of supporting body weight and rate at which this force is generated.<sup>18</sup> The rate of force generation can be estimated as total body weight divided by the time that a single foot contacts the ground during each stride.<sup>17-19</sup> Under controlled laboratory conditions, this approach can provide accurate estimates of the  $M_{LOCO}$ .<sup>19</sup>

The objective of this study was to compare TEE estimated using Tc-pedometry with that measured by the criterion DLW method. The test volunteers were U.S. Marines participating in a physically demanding dismounted infantry field training exercise where movement by foot was the dominant form of structured physical activity.

## MATERIALS AND METHODS

### *Test subjects*

The U.S. Marine Corps (USMC) test volunteers who participated in this study gave their free and informed written consent in accordance with relevant U.S. Army regulations regarding the use of volunteers in research. The investigators adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Eight male Marines [ $27 \pm 4$  years of age (mean  $\pm$  SD); weight =  $83.2 \pm 10.7$  kg; height =  $182.2 \pm 4.5$  cm; body fat =  $17.0 \pm 2.9\%$ ] were studied during the first 2 days of a 7-day USMC Infantry Officer Course field exercise. Five additional Marine test volunteer cohorts, who received tap water rather than DLW, provided urine samples that were used to monitor for any changes in baseline isotopic enrichment that might affect the precision of the DLW measurements.

Data presented here are from a 50-h period from day 1 (0500 h) to day 3 (0700 h) of a 7-day field exercise. The field exercise, which is designed to test the student's physical and mental performance during simulated combat, is part of the 10-week-long USMC Infantry Officer Course. Students commonly operate on limited sleep, march for extended periods of time while carrying heavy loads (15-60 kg), and consume one or two Meal-Ready-to-Eat (MRE) field rations per day where each MRE ration provides about 5.65 MJ (1,350 kcal).

Meteorologic conditions were temperate: ambient temperature = 19-31°C (range); black globe temperature = 20-44°C; relative humidity = 43-95%; wind speed = 0.2-3.8 m s<sup>-1</sup>.

*Resting energy expenditure (REE)*

REE was calculated for each Marine using a modification of the equation of Mifflin et al.<sup>20</sup>:

$$\text{REE (w)} = [10 \cdot \text{weight (kg)} + 6.25 \cdot \text{height (cm)} - 5 \cdot \text{age (years)}] \cdot 0.04843 \quad (1)$$

*Body weight, loaded weight, equipment, and clothing log*

Seminude body weight was measured at the start of the study using a calibrated balance accurate to  $\pm 0.05$  kg (Model 770, Seca, Hamburg, Germany). This balance was also used for daily measurements of total weight, which included all clothing, equipment, weapons, food, and water. Body fat was estimated pre- and post-study from abdomen circumference using an equation developed with U.S. Marine subjects similar to those in the present study,<sup>21</sup> that is,  $\text{FFM} = (40.99 + 1.0435 \times \text{BM}) - (0.6734 \times \text{abdomen})$ , where FFM = fat free mass in kg, BM = body mass in kg, and abdomen = waist circumference in cm measured at the level of the navel. Three sequential measurements of abdomen circumference were made on each test volunteer by the same investigator using a spring-loaded fiberglass anthropometric tape. Fat mass was calculated as body mass minus fat-free mass. Test volunteers kept a daily log of hour-to-hour changes in clothing and equipment. Hourly loaded weight was estimated for each subject by adjusting for changes in clothing and equipment noted in the equipment logs.

*Food intake and estimated thermic effect of food (TEF)*

Daily food intakes were calculated from individual collections of the various wrappers from ration items consumed on a given day, with the TEF estimated as 10% of total caloric intake. The food consumed consisted almost exclusively of MRE field rations. Metabolizable energy intake was calculated by factoring quantities of individual food items consumed against their caloric content (Nutritionist version 5; First DataBank, Inc., Hearst Corp., San Bruno, CA).

*Accelerometric assessment of  $M_{\text{LOCO}}$* 

Taylor and colleagues used high-speed cinematography and force platform methods to

show that the  $M_{\text{LOCO}}$  is primarily determined by the cost of supporting body weight and the rate at which this force is generated.<sup>18,19</sup> The rate of force generation can be estimated as total body weight divided by the time during each stride that a single foot was in contact with the ground ( $T_c$ ). At a given total body weight, increases in the speed of locomotion are associated with decreases in foot contact time, increases in the rate of force generation, and increases in the  $M_{\text{LOCO}}$ . Thus, a close approximation of  $M_{\text{LOCO}}$  may be obtained from measurements of total body weight and foot contact time.

The  $M_{\text{LOCO}}$  was calculated from total subject weight (including load carried), and time-series  $T_c$  measurements.<sup>17-19</sup>  $T_c$  values were measured using a prototype pedometer that attached to the boot laces (2.5 cm  $\times$  2.5 cm  $\times$  1.3 cm; 72 g) (Fitsense, Inc., Southboro, MA). This prototype device did not record raw accelerometric signals, but provided  $T_c$  and time of flight (loft time) during each stride by on-the-fly analysis of the rapid foot de-acceleration on heel strike, and the more subtle acceleration on toe-off. The reader is referred elsewhere for a more detailed description of the methodology, including an example of the accelerometer signal and validation of the accelerometrically determined  $T_c$  against  $T_c$  measured by force plate.<sup>22</sup> Equations for the relationship between total weight, accelerometrically measured  $T_c$ , and  $M_{\text{LOCO}}$  were generated for walking and running using published data<sup>22</sup> and unpublished data (personal communication) from P.G. Weyand and co-workers. The pedometers were worn continuously during the 50-h experiment.

Activity was classified into five categories: run, walk, slow walk, shuffle or "non-exercise activity thermogenesis" (NEAT), and no activity. Periods of running and walking were readily identified from  $T_c$  duration. Periods were classified as "slow walk" when heel strike was detected but not the more-subtle toe-off. The  $T_c$  for these slow walk periods was about 1,000 ms, and movement velocity was less than 0.894 m s<sup>-1</sup> (<2 mph). NEAT periods were defined as time gaps greater than 1.5 min among bouts of running, walking, or slow walking when the pedometer could not discern a heel strike or toe-off, but was unable to classify the period as

"no activity" because accelerometric evidence of activity was present. Although no single definition exists, NEAT typically refers to energy expenditure for everything that is not sleeping, eating, or volitional exercise, to include sitting, standing, maintaining non-recumbent body posture, changing body posture, fidgeting, and spontaneous muscle contraction. In the present study, the NEAT movement category, the most undefined of the movement categories, included any activities in which foot motion was present. The metabolic cost of a NEAT period was calculated as the average of REE plus the metabolic cost of standing, where the metabolic cost of standing with a load was calculated using the non-movement portion of the Pandolf equation.<sup>23</sup> Finally, periods when no accelerometric signal was present were classified as "no activity" with energy costs equal to estimated REE.

The equations in Table 1 were used to calculate the  $M_{LOCO}$  for each of the five activity categories. Individual daily TEE was calculated for each individual as the sum of calculated REE, TEF, and  $M_{LOCO}$  derived from total subject weight and  $T_C$  values. No attempt was made to correct TEE for upper body exercise or the effects of terrain grade. The range in elevations over the 9-km<sup>2</sup> area in the northwest quadrant of the USMC Base Quantico where the Marines trained elevations was about 9 m (126–135 m above sea level).<sup>24</sup>

#### Assessment of daily average TEE by DLW

The DLW method<sup>25</sup> is based on the assumption that after an initial oral dose of stable <sup>2</sup>H<sub>2</sub>O (deuterium oxide) plus H<sub>2</sub><sup>18</sup>O, the deuterium is eliminated from the body as water (<sup>2</sup>H<sub>2</sub>O),

whereas H<sub>2</sub><sup>18</sup>O leaves as both water (H<sub>2</sub><sup>18</sup>O) and exhaled carbon dioxide (C<sup>18</sup>O<sub>2</sub>). The rate of CO<sub>2</sub> production ( $V_{CO_2}$ ) is calculated from the difference in elimination rates of the two isotopes. Oxygen consumption and total metabolic energy expenditure are calculated from  $V_{CO_2}$  using a metabolic fuel quotient (FQ) (respiratory exchange ratio) calculated from food intake and body energy store combustion, and conventional calorimetric relationships.<sup>26</sup>

In this study, TEE<sub>DLW</sub> was measured using standard procedures.<sup>25,27–29</sup> Briefly, on the morning of day 0, the volunteers, who had refrained from eating or drinking for at least 12 h, reported to the testing area with a baseline sample of their first morning-void urine. After body weight was recorded and baseline saliva samples were collected, the eight subjects drank 0.30 g/kg of body weight of H<sub>2</sub><sup>18</sup>O (Isotec, Inc., Miamisburg, OH) and 0.09 g/kg of body weight of <sup>2</sup>H<sub>2</sub>O (MSD Isotopes, St. Louis, MO), as well as the 100 mL of tap water used to rinse the dose container. Saliva samples used to determine total body water (TBW) were collected 3 and 4 h after the initial dose of DLW. The subjects were free to eat and drink only after the final saliva sample was collected. First morning-void urine samples were collected at the beginning and end (day 1 and day 3) of the study period. All urine and saliva samples were stored in 4.5-mL tubes with silicone O-ring seals (Nunc, Roskilde, Denmark).

Isotopic analyses were performed as previously described.<sup>30</sup> Briefly, the <sup>18</sup>O abundances were measured by equilibration of fluid with CO<sub>2</sub>. Measurements were done in duplicate with an SD of  $3 \pm 10^{-5}$  atom percent (0.15‰). Deuterium abundances were measured by the

TABLE 1. METABOLIC COST OF LOCOMOTION EQUATIONS FOR EACH MOVEMENT CATEGORY

Movement category	Equation for estimating $M_{LOCO}$ (W)
Run	$M_{LOCO} = 4.517(W_{TOTAL}/T_C) - 378.33$
Walk	$M_{LOCO} = 4.312(W_{TOTAL}/T_C) - 269.62$
Slow walk	$M_{LOCO} = 4.312(W_{TOTAL}/T_C) - 269.62$ where $T_C = [\text{Mean walk } T_C + (3SD)]$
Shuffle/NEAT	$M_{NEAT} = \{[1.5 \cdot W_b + 2.0(W_b + L)(L/W_b)^2] - REE/2\}$
No activity	$M_{LOCO} = 0$

$M_{LOCO}$  = metabolic cost of locomotion (in W),  $W_{TOTAL}$  = total weight (in kg),  $W_b$  = body weight (in kg),  $T_C$  = foot-ground contact time (in s),  $M_{NEAT}$  = metabolic cost of non-exercise activity thermogenesis,  $L$  = load (in kg), REE = resting energy expenditure (in W).

zinc reduction method. Measurements were performed in triplicate with an SD of  $1.7 \pm 10^{-5}$  atom percent (1.2‰). Isotope enrichments were calculated by taking the arithmetic difference between the per mil enrichment of each sample and the respective pre-dose sample. The ratio of excess isotope was calculated and converted to atom percent excess.

Daily TEE was calculated using the linear regression method.<sup>28</sup> Baseline isotopic <sup>2</sup>H and <sup>18</sup>O abundances were monitored in five cohorts who received tap water instead of DLW. The rate of O<sub>2</sub> production was calculated from CO<sub>2</sub> production using a calculated FQ.<sup>26</sup> That is, a metabolic FQ was calculated from the macronutrient composition of the rations consumed and the magnitude of the estimated energy deficit (TEE - food intake), assuming the energy deficit was met from the body's glycogen stores (estimated as 300 g) and the body's fat stores, which were assumed to be composed of 90% fat and 10% protein. Standard factors were used to correct for isotope fractionation in respiratory and cutaneous water efflux.<sup>11,29</sup> The use of placebo cohorts to monitor for any changes in background isotopic enrichment helped ensure the accuracy of the TEE<sub>DLW</sub> measurements.<sup>28</sup> The benchmark DLW method used to measure TEE is known to be accurate.<sup>25</sup> Although the precision of the TEE<sub>DLW</sub> measurements was reduced by the relatively short 2-day study period, Schoeller<sup>27</sup> suggested the precision of the DLW method, in a 25-year-old male with a 2-day study period at isotopic doses similar to those in the present study, should be <1 MJ/day.

#### Data analyses

The data were analyzed using Student's *t* test, linear correlation and regression, and an Altman-Bland plot,<sup>31</sup> which shows the difference between individual measures by the two methods plotted against the mean of the two methods. The mean error was calculated as the SD of the difference between TEE<sub>PEDO</sub> and TEE<sub>DLW</sub>, while total error was calculated as  $[\sum(\text{TEE}_{\text{PEDO}} - \text{TEE}_{\text{DLW}})^2 / (n - 1)]^{1/2}$ .

## RESULTS

The Marine test volunteers carried loads of  $30.0 \pm 6.9$  kg (range = 17.1–39.9 kg). The

estimated average metabolic FQ was 0.804. Calculated REE was  $7.71 \pm 0.51$  MJ/day (range = 6.84–8.56 MJ/day) and constituted  $52 \pm 3.5\%$  of TEE<sub>DLW</sub>. Baseline isotopic enrichments did not change significantly, and thus no baseline enrichment corrections were made to TEE<sub>DLW</sub> calculations. In addition, TEE<sub>DLW</sub> was not corrected for the estimated 2% change in TBW, given that the influence of changes in pool size on TEE<sub>DLW</sub> will be less than 2% if the pool size changes less than 4%.<sup>27</sup>

Logbook entries indicated the subjects engaged in a limited amount of upper body exercise: that is, 2 h of practice throwing hand grenades, 1 h of preparation of a hasty defense (a defense organized when time is limited and characterized by improvement of the natural defensive strength of the terrain by utilization of foxholes, emplacements, and obstacles), and loading a truck.

Food energy intake was  $5.72 \pm 1.14$  MJ/day (range = 3.80–7.02 MJ/day).

TEE<sub>DLW</sub> equalled  $15.27 \pm 1.65$  MJ/day and ranged between 13.29 and 17.80 MJ/day, with the average TEE<sub>DLW</sub>/REE ratio being  $1.99 \pm 0.26$  (range = 1.73–2.32). TEE<sub>PEDO</sub> equalled  $15.29 \pm 0.83$  MJ/day (range = 14.26–16.67 MJ/day). Mean bias (TEE<sub>PEDO</sub> - TEE<sub>DLW</sub>) was 0.02 MJ, and both mean error and total error were 1.83 MJ. The mean individual TEE<sub>DLW</sub> and TEE<sub>PEDO</sub> values over the 2-day experimental period are shown in Table 2.

#### Pedometry

The Tc frequency distribution is shown in Figure 1. The Marines averaged  $6,672 \pm 987$  steps/day (range = 5,389–8,258). This suggests the Marines traveled about  $5.3 \pm 0.8$  km/day (approximate range = 4.3–6.6 km/day), assuming the distance traveled during each step is about 0.8 m. The relatively limited number of steps per day was presumably largely due to the heavy loads carried by the Marines and the associated increase in the per-step cost of locomotion. Additionally, at slow rates of movement the Tc pedometer may have classified very slow steps as "shuffle/NEAT," thereby decreasing the total step count. The distribution of time spent across the different

TABLE 2. DAILY TEE VALUES MEASURED USING THE DLW METHOD ( $TEE_{DLW}$ ) AND THE FOOT-GROUND CONTACT PEDOMETRY METHOD ( $TEE_{PEDO}$ ) (MJ/DAY) FOR EIGHT MALE MARINE TEST VOLUNTEERS DURING A 2-DAY FIELD TRAINING EXERCISE

Subject number	$TEE_{PEDO}$	$TEE_{DLW}$	Difference	Absolute difference
1	16.17	17.81	-1.64	1.64
2	14.26	16.67	-2.41	2.41
3	15.17	14.72	0.45	0.45
4	16.67	15.29	1.38	1.38
5	14.85	14.31	0.54	0.54
6	15.77	13.29	2.48	2.48
7	14.81	13.37	1.44	1.44
8	14.61	16.70	-2.09	2.09
Mean	15.27	15.29	0.02	1.55
SD	1.65	0.83	1.83	0.77

movement types, expressed as a percentage of total time, is shown in Figure 2. Activities other than locomotion (i.e., shuffle/NEAT category), and walking (walk category), were the predominant physical activities. NEAT activities occupied about two-thirds of the subject's time, and accounted for  $51 \pm 9\%$  of TEE [composed of a  $15 \pm 6\%$  contribution from activity-related energy expenditure (AEE) and a  $35 \pm 2\%$  contribution from REE]. Remarkably little time or metabolic energy was spent in inactivity (apparent sleep).

The group means for  $TEE_{DLW}$  and  $TEE_{PEDO}$ , compared using a paired Student's  $t$  test, did not differ significantly ( $t = -0.03$ ,  $df = 7$ ,  $P = 0.98$ ) ( $r = 0.17$ , not significant). Although the correlation was weak, the Altman-Bland plot (Fig. 3), showing the difference between methods ( $TEE_{PEDO} - TEE_{DLW}$ ) plotted against the mean of the two measures, illustrates the small bias between measures. Similarly, a comparison of  $M_{LOCO}$  with ( $AEE_{DLW}$ ) ( $AEE_{DLW} = TEE_{DLW} - TEF - REE$ ), showed a weak correlation of individual values but a close correspondence of

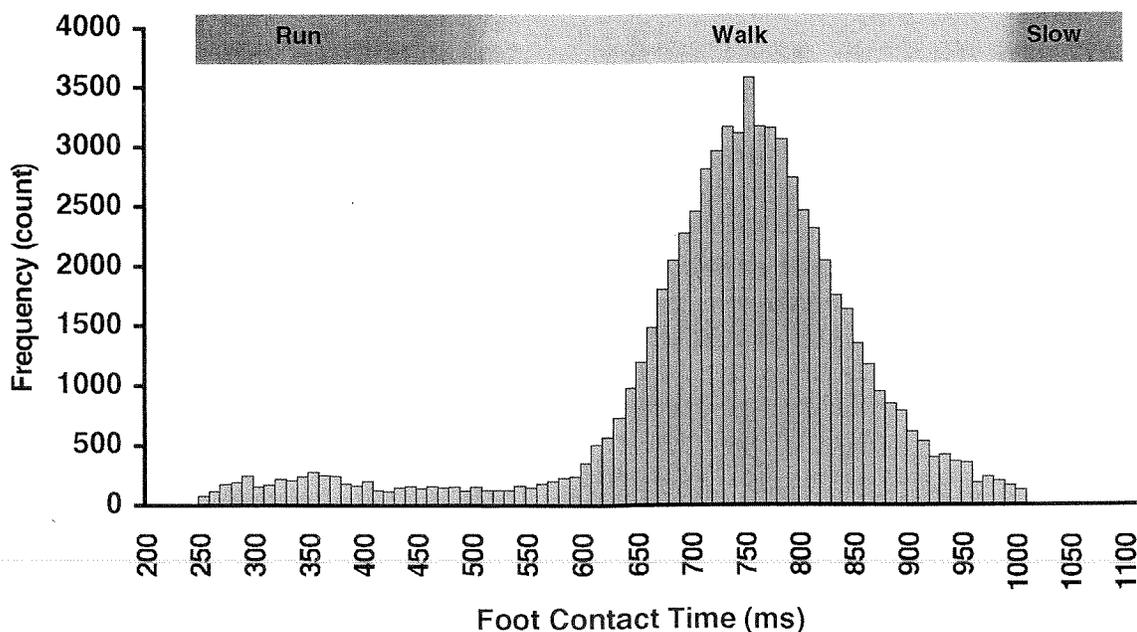


FIG. 1. Frequency distribution of accelerometrically measured Tc values measured over a 50-h experimental period in eight U.S. Marines participating in a field training exercise.

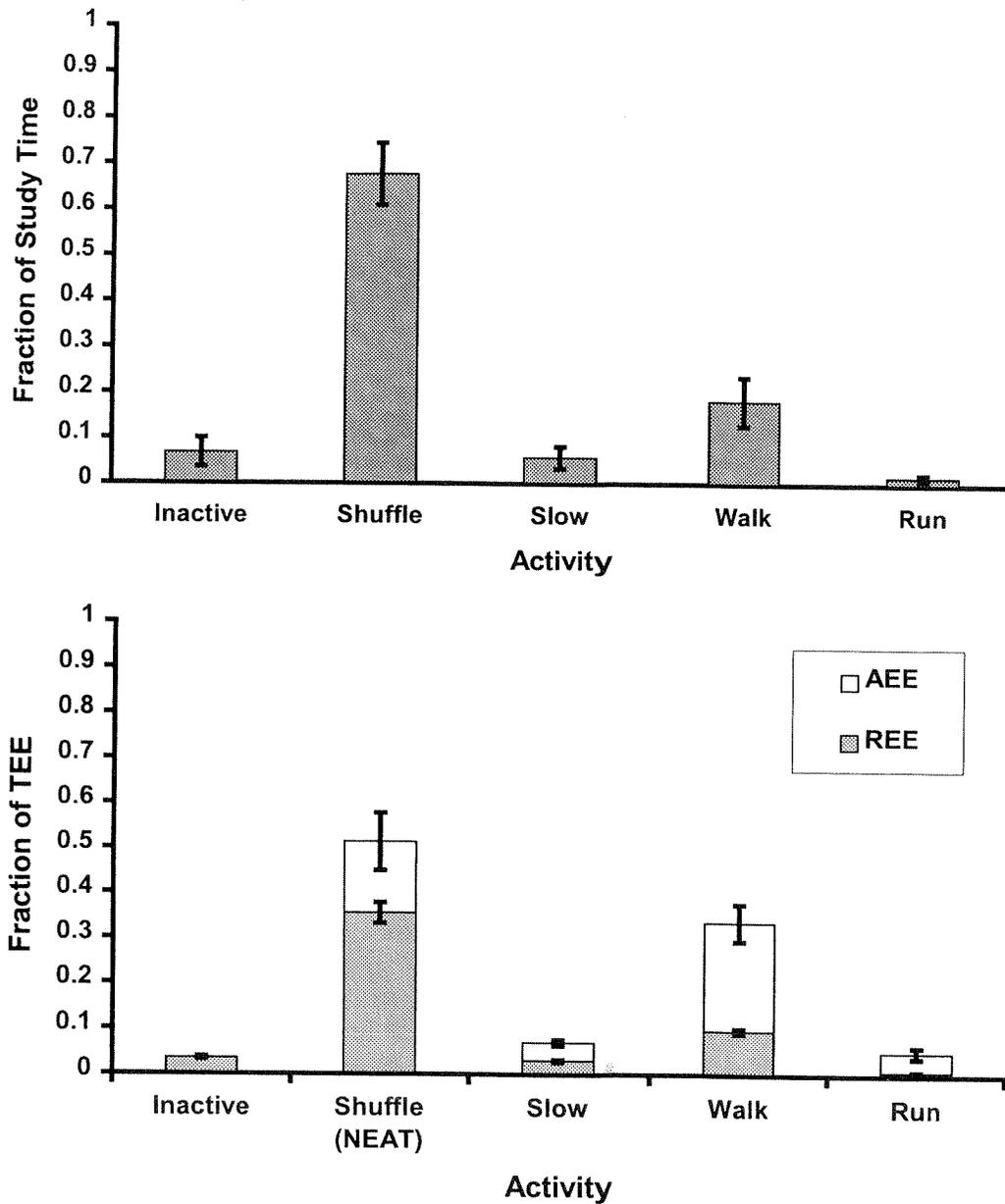


FIG. 2. Activity distribution, expressed as a fraction of study time or fraction of TEE for various categories of physical activity. The "shuffle" category represents NEAT. Data are from eight male Marine test volunteers over a 2-day (50-h) field training exercise. Mean values with SD are shown for fraction of study time, AEE, and REE.

group mean values ( $AEE_{DLW} = 7.00 \pm 1.85$  MJ/day,  $M_{LOCO} = 7.02 \pm 0.75$  MJ/day) (paired  $t = 0.029$ ,  $df = 7$ ,  $P = 0.98$ , not significant) ( $M_{LOCO} = 0.0951 \times AEE_{DLW} + 6.35$ ;  $r = 0.23$ ).

## DISCUSSION

The present findings indicate that the Tc-pedometry method can provide valid estimates of

the average TEE of small groups of active subjects where walking is the dominant activity. We found that the overall difference between  $TEE_{PEDO}$  and  $TEE_{DLW}$  groups was insignificant and averaged less than 1%. Fogelholm et al.,<sup>4</sup> in a study of 20 overweight women, compared TEE estimated by HR monitoring and by commercial accelerometer (Caltrac, Muscle Dynamics, Torrance, CA) with TEE measured by DLW. They reported greater inaccuracy in es-

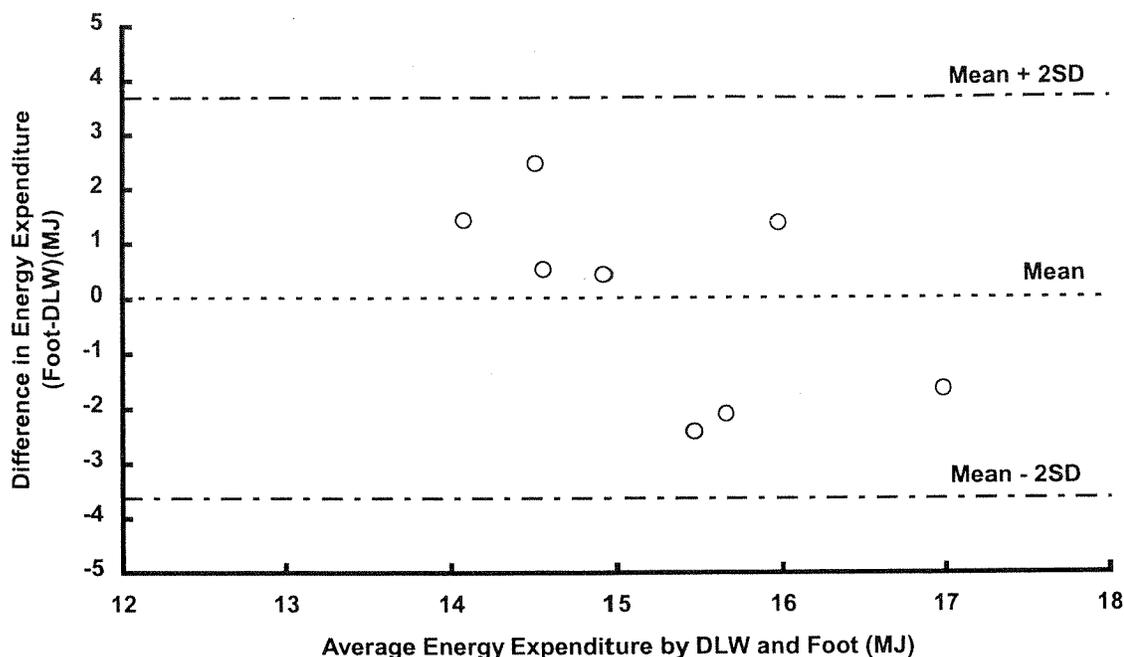


FIG. 3. Altman-Bland plot<sup>31</sup> showing the difference in TEE between the pedometry and DLW methods ( $TEE_{PEDO} - TEE_{DLW}$ ) plotted against the mean of the two measures. Eight male Marine test volunteers were studied over a 2-day field training exercise. Mean bias (i.e.,  $TEE_{PEDO} - TEE_{DLW}$ ) was 0.02 MJ, and the mean error (SD of individual differences between  $TEE_{PEDO}$  and  $TEE_{DLW}$ ) was 1.83 MJ.

timating individual differences ( $\sim 3.7$  vs. 2.5 MJ/day) and a greater error as a percentage of TEE ( $\sim 16\%$  vs. 12%) than in the present study. However, the error (SD of the difference between methods) and the bias (mean difference between the alternative methods and  $TEE_{DLW}$ ) were similar for HR and commercial accelerometer methods,<sup>4</sup> and for the accelerometer-based Tc-pedometry method used in the present study.

Attempts to estimate TEE using conventional pedometers, that is, simple devices that provide only the total number of steps per day rather than time series data, have generally been unsuccessful.<sup>4,32</sup> This is presumably due to (a) the lack of a clear method of converting steps per day, a measure of physical activity, to metabolic energy expenditure, and (b) an inability to differentiate inactivity, activity other than locomotion, and locomotion.

The Tc-pedometer method has a number of advantages. Tc values are easily converted to  $M_{LOCO}$  values knowing total subject weight.<sup>19</sup> In addition, the Tc-pedometer approach does

not require individual calibration, can be used to monitor relatively low-intensity locomotion, and uses simple algorithms to estimate TEE. In comparison, the HR method requires laborious generation of individual HR-to- $VO_2$  calibration curves to convert HR data to metabolic cost, and the method is not suited to monitoring the energy cost of low-intensity activities. Commercial devices that rely on accelerometers for data collection, such as the Caltrac, commonly use proprietary equations to estimate TEE.

Notably, the Tc-pedometer method, by combining pedometry and accelerometric activity monitoring, can be used to differentiate major categories of activity: locomotion, NEAT, and inactivity. A similar use of the locomotion-NEAT-inactivity categorization is used to present data collected using another recently developed research-grade accelerometric pedometer (AMP-331, see <http://www.dynastream.com>; DynaStream, Inc., Cochrane, AB, Canada). NEAT in the present study included energy expended in activities such as occupying defensive positions, planning missions, and reviewing mission

performance. Inevitably, NEAT includes difficult-to-characterize activities. To provide a more complete account of NEAT, investigators have used inclinometers to monitor body posture and to detect changes in body posture.<sup>33</sup> Similarly, by quantifying the time spent in various categories of locomotion, Tc-pedometry helps define NEAT more completely.

NEAT was an important part of the time and energy budget of our physically active, sleep-restricted Marines, accounting for about two-thirds of the time and half the TEE of the subjects. The observed variability and magnitude of NEAT among the Marines are consistent with the results of a classic whole-room respirometer study that found NEAT varies widely and can be a significant component of TEE.<sup>34</sup> Also, Levine et al.<sup>35</sup> found that NEAT appears to play an important role in mediating TEE and weight gain in response to overeating. NEAT may also play a role in preventing obesity.

The Tc-pedometer method can help meet the need to accurately estimate the energy cost of walking and running, major components of normal physical activity. However, there are limits. The complex nature of physical activity prevents any single instrument from being suitable for all conditions. For example, Tc-pedometry would be modestly relevant among individuals primarily engaged in activities other than walking and running. The Marine test volunteers are clearly distinct from generally older, less-fit, less-physically active, obese and diabetic populations. Nevertheless, the present results seem instructive, and the methods presented here can be readily applied to estimating TEE in other populations if estimates of dietary intake and total weight can be obtained.

It is reasonable to argue that the amount of volitional exercise and the magnitude of NEAT are related to the likelihood of obesity and Type 2 diabetes. Can innovative ambulatory monitors, such as Tc-pedometers, activity monitors, and inclinometers, be used to explore these relationships? Aerobic fitness, which reflects the amount, duration, and intensity of antecedent physical activity, can be assessed using Tc-pedometry without the

need for expensive and cumbersome equipment to measure gas exchange (indirect calorimetry).<sup>22</sup> Ambulatory monitors can also be used to assess TEE and the distribution of locomotion-NEAT-inactivity across patient populations. Ambulatory monitors could also be used to reward increased activity, or perhaps even increased NEAT. Finally, knowing the intensity and duration of activity may make it possible to estimate individual metabolic fuel utilization, allowing a patient's diet to be liberalized or constrained as a function of physical activity.

In conclusion, our findings indicate that Tc-pedometry can provide valid estimates of the mean TEE of small groups of physically active subjects where walking is the dominant activity. This scalable new approach to assessing physical activity patterns, quantifying the  $M_{LOCO}$ , and quantifying daily TEE, deserves further study.

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## Analysis

# Bioenergetics of Animal Locomotion: Lessons for Expedient Monitoring in Human Fitness and Weight Management

COL. KARL E. FRIEDL, Ph.D.

**B**ASIC PRINCIPLES of animal physiology can provide valuable insights to complex systems. Such is the case with foot-ground contact time ( $T_c$ ) and bioenergetics. Modeling energy costs of human movement is complicated, requiring articulated models to account for biomechanical efficiencies, elastic elements that cyclically store and release energy, and the various groups and types of muscles appropriate to the type of locomotion. However, overarching principles governing the metabolic cost moving a body mass through space and time suggest total mass (body weight and load weight) and  $T_c$  (the time during each step that the foot is in contact with the ground) present a much simpler solution to estimating the energy costs of locomotion. Reed Hoyt and Peter Weyand applied an empirical observation that the metabolic cost of walking or running varied as a function of the ratio of body weight ( $W_b$ ) and  $T_c$  to estimate the metabolic costs of walking or running ( $M_{loco}$ ).<sup>1</sup> In this issue of *DT&T*,<sup>2</sup> the  $T_c$  technique for estimation of  $M_{loco}$  has undergone further validation for use in free-ranging humans moving over level ground at different speeds. For an extra challenge, these tests involved Marines carrying backpack loads in rigorous training.

The idea for this measurement approach came from studies at Harvard University's Concord Field Station in Bedford, MA, where

cross-species studies seek to improve our understanding of the principles of biomechanics and bioenergetics from the cell and tissue level to whole organisms. Energy expenditure and locomotor mechanics have been measured for terrestrial birds, mammals, and even some reptiles with a wide variety of locomotory strategies, ranging from tiny kangaroo rats running on a treadmill to trotting elephants accompanied by a golf cart modified to collect gas expired from the elephant's trunk. All of the animals tested fall in on a single curve relating mass,  $T_c$ , and energy expenditure; locomotion is more economical with increasing mass of various species, no matter how ungainly some larger creatures may seem.<sup>3</sup> The Concord Field Station investigators observed that the same size dependence they initially quantified for the rate of metabolic energy expenditure also applied to the rates at which the different-sized animals completed their strides. For example, at equivalent speeds such as the trot-gallop transition where the relative proportions of the contact and aerial portions of the stride are the same, the per-stride costs of the large and small creatures are also the same. This observation raised the possibility that the greater mass-specific metabolic rates of smaller animals might be a direct function of the shorter periods of their strides. The Concord Field Station crew considered the likely candidate to be the con-

tact portion of the stride during which ground force must be applied to support the body's weight. Subsequent investigation demonstrated this was indeed the case. Regardless of the animal's size or speed, mass-specific metabolic rates are a constant multiple of the inverse period of foot-ground contact that the investigators used to estimate the rate of ground force application.<sup>4</sup> This led to the understanding that on level ground, the primary metabolic costs are those required for the muscles to support body weight.<sup>5</sup> The  $T_c$  method is increasingly accepted,<sup>6</sup> and is well suited to field application because the equation requires only two inputs: body weight and  $T_c$  ( $M_{loco} = Wb/T_c \times \text{Constant}$ ).

The actual measurement device first devised by Hoyt and co-workers measured  $T_c$  using force-sensitive resistors under the toe and heel and was validated with treadmill walking and running.<sup>7</sup> Field tests of the prototype hardware were disheartening. The initial conceptions required an imprint of each soldier's foot so that special insoles could be constructed to house an inside-the-boot monitor. A collaborative field trial was conducted with Norwegian cadets going through an extreme endurance course. Wires to the connectors broke, data downloads failed, and the inserts proved to be an irritant to the subjects. These technical problems were solved without international incident, and eventually led to the accelerometric outside-the-boot lace-up prototype footstrike monitor. This has since been used in a variety of military physiological monitoring studies along with other sensors such as the wrist-worn actigraph to complement sleep/wake history in studies such as one of senior military leaders involved in high-intensity military planning activities, and another study involving a squad of infantry soldiers in a field training exercise.<sup>8</sup>

In this latest validation test by Hoyt et al.,<sup>2</sup> activity periods were classified into categories of locomotion that determined the method of energy estimation. The metabolic cost of running and walking were estimated from total weight and the time between the detection of heel strike and toe off (foot down/foot up). Slow walk was detected by a heel strike with no detectable toe off, with energy costs esti-

mated from some assumptions about  $T_c$ . Shuffle [or "non-exercise activity thermogenesis" (NEAT)] periods were detected by accelerometer activity without discernible heel or toe activity, with energy costs estimated as the metabolic cost of standing. Rest was when no accelerometer activity was present and no additional energy costs beyond resting metabolic rate (RMR) were estimated. These estimates were summed to estimate total  $M_{loco}$ . Comparisons were made to total daily energy expenditure (TDEE) measured using doubly labeled water (DLW) ( $^2\text{H}_2^{18}\text{O}$ ). To do this, the investigators had to estimate the missing components of TDEE that are not estimated from  $M_{loco}$ , including RMR and thermic effects of food (TEF). Although follow-up studies are certainly needed, and a number of assumptions were required to make this comparison, the results were quite good with the mean error in TDEE between  $T_c$  and DLW estimated at 12%. This was a highly active group with relatively little sleep time, and average energy expenditure of 15.3 MJ/day (3,670 kcal/day) over the 50-h period of their exercise. This also included average carried weights of 30 kg (also factored into the total mass for  $T_c$  computations).

There are numerous gadgets now marketed for energy expenditure measurements with a variety of uses and usefulness. One should clearly distinguish the components of metabolic costs that the methods attempt to measure. Portable calorimeters that have a breathing apparatus and a backpack gas analyzer provide estimates of total energy expenditure, including those components associated with locomotion. These have been used to assess metabolic costs associated with various typical soldier tasks such as carrying stretchers and carrying backpack loads in various types of constricting clothing, etc. This method is estimated to provide accuracy within 5% alongside of treadmill testing for  $\text{VO}_{2\text{max}}$ .<sup>9</sup> Heart rate, calibrated to the individual, provides some reasonable estimates of total energy expenditure in discrete time periods but can be unreliable in largely sedentary populations. Both calorimetry and heart rate reflect something about overall metabolic rate, combining RMR, TEF, NEAT, and energy costs of activity (including locomotion). Pedometry, accelerometry, and  $T_c$

measurement each provide estimates of metabolic costs associated with body motion. The type of activity captured obviously depends on the location of the sensors. Standard pedometry, in which only a step count is recorded, is one of the least reliable of energy measurement methods and provides more value as a motivational tool for patient exercise than a useful energy measurement device. However, accelerometer-based pedometers capable of reliably recording time series data over days appear to be scientifically useful.<sup>10</sup> Accelerometry has been used primarily on wrists and hips to estimate overall body motion energy expenditure and may work best in combination, as described in the last issue of *DT&T*.<sup>11</sup> Compared with measures of oxygen uptake in a laboratory, commercially available accelerometers have been reported to have errors averaging 10–20%; much better accuracy was reported by Chen et al.,<sup>11</sup> who used multiple accelerometers. The  $T_c$  method provides an alternate path to accurately estimate muscle force generation and  $M_{loco}$ , making it potentially more accurate for measurement of this specific component; upper body motion captured by multiple accelerometers or heart rate techniques is not measured with this approach. There is great value in assessing weight-bearing exercise, as the most important component of fitness and weight management programs, as well as for specific exercise objectives such as stimulating bone mineral accretion. As Hoyt et al.<sup>2</sup> point out, this may also provide a novel approach to estimating NEAT, a potentially important factor in weight management.

In future developments, if high-tech accelerometer-based pedometers capable of recording data over days could be coupled with a tri-axial accelerometers or supersensitive altimeters to detect movement up or down inclines, including ladders and stairs, this might resolve some variability expected from work on uneven surfaces. Technologies that put the sensor back inside the shoe to measure regional pressures on the foot (“pedobarography”) may also provide very useful information for noninvasive monitoring of energetics of locomotion, with a complete picture of type of activity as well as ground reaction forces involved.

The research effort on locomotion continues with Department of Defense-supported research in Peter Weyand’s lab at Rice University. One hope is that this type of research will provide a basis for a non-running test of fitness that could be applied both to the military and to patients with diabetes, providing a simple and accurate method to assess overall changes in physical fitness levels. As an example, Weyand, Hoyt, and colleagues recently reported that combining  $T_c$  with heart rate monitoring produced accurate estimates of maximal aerobic power.<sup>12</sup> It would be useful to know if changes in  $T_c$  and heart rate relationships over periods of stable monitoring taken weeks or months apart could reflect changes in fitness levels, or if acute alterations during military field operations might provide an index of thermal or dehydration. Providing noninvasive “smart shoe” technologies that provide feed back about energy expenditure as well as improvements in fitness could encourage soldiers and patients with diabetes to engage in physical training programs.

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