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ACCURACY OF PREDICTIVE EQUATIONS FOR METABOLIC COST OF LOCOMOTION WHILE CARRYING EXTERNAL LOAD

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ABSTRACT

Introduction: Energy cost estimation of dismounted military movements is of significant importance for a number of reasons, including optimal performance planning and to ensure individual safety. Predicting energy costs during military road marches, i.e., locomotion, requires insights into key factors such as: body mass, clothing, any additional load carried, walking velocity, surface grade, and other terrain features (e.g., pavement, gravel, snow). **Methods:** Physiological measures and measures of oxygen uptake (VO_2) were collected from nine individual Soldiers (age, 22 ± 4 (SD) y; wt, 76.44 ± 10.67 kg; ht, 175.00 ± 10.14 cm; body fat, 23.4 ± 5.8%; VO_{2max}, 49.22 ± 3.33 ml•kg^{-1}•min^{-1}), during treadmill exercise in an environmental chamber. Volunteers walked at two different work intensities, approximately 350 and 540 W: under warm-humid (air temperature (Ta) 25°C, 50% relative humidity (RH)), hot-humid (35°C, 70% RH), and hot-dry (40°C, 20% RH) environmental conditions. Observed VO_2 values, in W, were compared to predicted total energy costs from four predictive equations using the root mean square error (RMSE), mean absolute error (MAE), and correlation coefficient (R^2) values. **Results:** Analyses showed predictions were in close agreement with measured values, with RMSE ranging from 19.56 to 38.16 W, MAE from 15.71 to 28.9 W, and R^2 from 0.86 to 0.96. **Conclusion:** The results indicate that for the specified test conditions, metabolic estimation equations can be used to accurately predict energy expenditure of walking locomotion. These equations accurately predict energy costs when individual differences exist in external load, walking velocity, moderate differences in grade increased surface grade, and different levels of thermal stress.

Keywords: energy expenditure, exercise, predictive equations, modeling, human locomotion.

INTRODUCTION

Dismounted military operations typically involve walking while carrying heavy loads, moving over complex terrain, and in varied environmental conditions [1]. It is well established that carrying heavy loads increases the risk of adverse effects on the individual and their performance [2]. Given the complex nature of these activities, it is important for mission planning and on-the-move decision making to be able to predict energy costs for each operation. An energetics-centric approach to mission planning can be a useful quantitative method for predicting optimal work-rest cycles, ensuring safety, providing an understanding of nutritional demands, and finding a balance between energy cost and performance.

When compared to athletes, military operations are typically lower intensity but generally longer in duration (e.g., <50% of VO_{2max} versus 60-80%, and days versus hours). This difference is important to note, as work intensity over time plays a significant role in the cumulative physiological strain and energy expenditure for individuals [3]. Given the distinct differences between athletics and military operations, there is a legitimate rationale for pursuing separate research efforts that focuses on the specific challenges faced by each population. The sports community has well established methods for estimating metabolic cost for athletes, such as the American College of Sports Medicine (ACSM) equations [4]. However, these methods typically do not take into account mixed terrain or an external load. In recognition of this disparity, military-specific equations have been developed by Givoni and Goldman [5], Pandolf et al. [6], and Santee et al. [7].

The purpose of this paper is to compare predictions based on these four methods to laboratory collected VO_2 data from Soldiers wearing external loads, walking at different speeds, on level and moderately inclined grades, and in several different thermal environments.

METHODS

Volunteers

Volunteers for this study included nine active duty male Soldiers (age, 22 ± 4 years (mean ± standard deviation (SD)); body mass, 76.44 ± 10.67 kg; height, 175.00 ± 10.14 cm; body fat, 23.4 ± 5.8%; VO_{2max}, 49.22 ± 3.33 ml•kg^{-1}•min^{-1}. Prior to study participation, each volunteer was briefed on the purpose, risks, and potential benefits of the study and gave written informed consent. The study was approved by both the Scientific Review Committee and Institutional Review Board (SRC and IRB) at the U.S. Army Research Institute of Environmental Medicine (USARIEM) (Natick, MA).

Procedures

Test volunteers participated in two bouts of treadmill walking on each test day, at two different work intensities. The two-phased test sessions were repeated in three different sets of environmental conditions: warm-humid (air temperature (Ta) 25°C, 50% relative humidity (RH), hot-humid (35°C, 70% RH), and hot-dry (40°C, 20% RH). The three days of testing in the 3 test environments, provided results for 6 exercise bouts, 3 at moderate intensity (~350 W) and 3 at higher intensity (~540 W) [8]. During each exercise session, volunteers walked for 60 minutes at two different set speeds, specifically tailored to each individual with the goal of maintaining metabolic work rates of approximately 350 and 540W. During the first, lower intensity bouts, individuals walked between 1.01 and 1.34 m/s (1.10 ± 0.08 m•s^{-1}), at level grade (0%). For the

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second, higher intensity bouts, speeds were increased to between 1.23 and 1.56 $m\cdot s^{-1}$ (1.3 ± 0.09 $m\cdot s^{-1}$) and grade was increased to between 2.5 and 4.5% (3.67 ± 0.59%).

Clothing

Volunteers each wore properly sized Army Combat Uniform (ACU), body armor with front, back, and side ballistic plates, Kevlar helmet, and running shoes. The total additional weight of the individual clothing and equipment ranged from 18.53 to 25.76 kg (20.92 ± 1.97 kg).

Metabolic Rate Measurement

Expired gas samples were collected using Douglas bags during rest periods, immediately prior to exercise bouts, and 20 minutes into each exercise bout. Each expired air sample was analyzed to obtain oxygen uptake (VO_2) using a metabolic cart (True One 2400 Metabolic Measurement System, Parvo Medics; Sandy, UT).

Predictive Equations

Previous work outlining various equations for estimating metabolic cost of locomotion was used as a starting point for this comparison [9]. The four equations evaluated are overviewed in Table 1 below.

Statistical Analyses

Statistical analyses were performed using SAS 9.3 statistical software (SAS Institute Inc., Cary, NC). Descriptive statistics are presented as means ± SD. Root mean square error (RMSE) and mean absolute error (MAE) were used to compare the predictions from each equation to the measured (actual) data. Using the RMSE equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

where d_i is the difference between observed and predicted metabolic cost for each individual (W), and n is the number of data points. The MAE being the average of the absolute errors within the predictions, in the equation:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n} |e_i|$$

where f_i is the predicted value, y_i is the actual value, and e_i is the absolute error.

Table 1. Overview of metabolic cost prediction models.

Model	Unit	Equation
GG [5]	$kcal\cdot hr^{-1}$	$\eta\cdot(M + L)\cdot[2.3 + 0.32\cdot(S - 2.5)^{1.65} + G(0.2 + 0.07\cdot(S - 2.5))]$
PE [6]	W	$1.5\cdot M + 2.0\cdot(M + L) + \eta\cdot(M + L) \cdot (1.5\cdot S^2 + 0.35\cdot S\cdot G)$
ACSM [4]	$ml\ O_2\cdot kg^{-1}\cdot min^{-1}$	$0.1\cdot S + 1.8\cdot S\cdot G + 3.5$
S-DG [7]	$ml\ O_2\cdot kg^{-1}\cdot min^{-1}$	$(0.661\cdot S+0.115)\cdot 3.28\cdot(M + L)+71.1+2.4\cdot((M+L)\cdot 9.81\cdot S\cdot G)$

ACSM = American College of Sports Medicine model [4]; G = grade (%); GG = Givoni & Goldman model [9]; L = external load (kg); M = body mass (kg); η = terrain factor; PE = Pandolf et al. model [6]; S-DG; Santee et al. model [7]; S = speed ($m\cdot min^{-1}$ for ACSM, $km\cdot hr^{-1}$ for Givoni and Goldman, $m\cdot s^{-1}$ for Pandolf et al. and Santee et al.)

RESULTS

Table 2 contains descriptive statistics for metabolic rate observations and estimations as well as model performance indicators. The ACSM model was the only model to have a positive bias as each other model underestimated the observed metabolic rate. The PE model had the strongest performance out of the four models with the lowest RMSE (20 W) and MAE (16 W) as well as the highest R^2 (0.96).

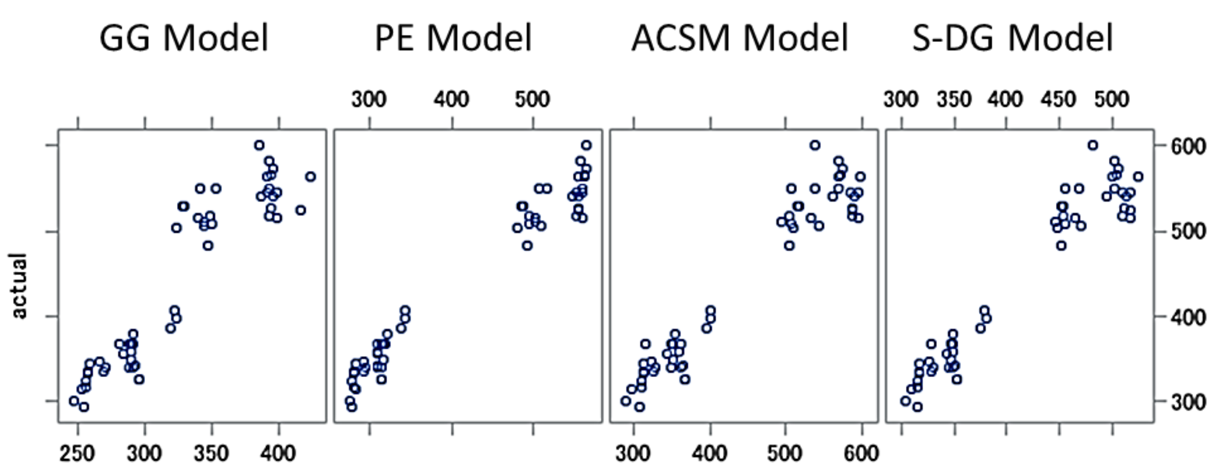
Conversely, the GG model had poorest estimation accuracy with the highest RMSE (38 W) and MAE (29 W) along with the lowest R^2 (0.86). Figure 1 displays scatter plots of metabolic rate observations versus estimations (W) from each model.

Table 2. Comparison of observed metabolic rate (W) and metabolic rate estimations from each model for Walk 1, Walk 2, and Total.

	Walk 1			**Walk 2**			**Total**					
Metabolic Rate	**Mean**	**± SD**	**Range**	**Mean**	**± SD**	**Range**	**Mean**	**± SD**	**Range**	**RMSE**	**MAE**	**R^2**
Observed	347	± 28	294 – 408	537	± 28	483 – 601	440	± 100	294 – 601	–	–	–
GG [5]	281	± 22	248 – 325	374	± 30	325 – 424	327	± 53	248 – 424	38	29	0.86
PE [6]	305	± 20	275 – 344	532	± 31	480 – 564	416	± 117	275 – 564	20	16	0.96
ACSM [4]	342	± 31	290 – 402	552	± 35	494 – 597	445	± 111	290 – 597	27	20	0.93
S-DG [7, 10]	338	± 21	303 – 380	486	± 27	446 – 525	411	± 78	303 – 525	26	20	0.93

SD = standard deviation; RMSE = root mean square error; MAE = mean absolute error; R^2 = coefficient of determination; GG = Givoni & Goldman (1971); PE = Pandolf et al. (1977); ACSM = American College of Sports Medicine (2000); S-DG = Santee et al. (2001) and Danielsson and Grambo (2003).

Figure 1. Scatter plots of metabolic rate observations versus estimations (W) from each model.



GG = Givoni & Goldman model (1971); PE = Pandolf et al. model (1977); ACSM = American College of Sports Medicine model (2000); S-DG = Santee et al. (2001) and Danielsson and Grambo model (2003).

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DISCUSSION

As expected from previous reviews, each of the selected predictive methods compared well with the measured data (Table 2 and Figure 1). Interestingly, while not the best performing method, the addition of external load to the total mass in the ACSM equation seemed to work almost as well (R^2 = 0.86) compared to the other methods. While each of these equations estimate energy costs reasonably well, it is important to note that the types of clothing worn can cause an increase in energy demand that cannot be explained by weight alone (e.g., ergonomic impediments) [11-12]. The clothing effect may increase the observed energy costs, whereas the four equations do not specifically compensate for clothing effects. The only mean predicted values that exceed the observed values are for the ACSM model. However, the other three equations were developed using data from Soldiers wearing military clothing.

Despite the study exercise trials being conducted within three distinct environments, no significant differences were observed between conditions and energy costs. Thus for equation inputs and comparison of predicted and observed VO_2 data, it was not necessary to separate the data and results by environment. Mass values varied slightly between test days. Individual volunteer parameters and test conditions were used as input into the four models, in W, to predict energy costs. The results for the four equations were compared to the observed VO_2 data. In addition, using a random selection of 16 data training points (W), a linear regression model was created and compared to the total measured data (53 data points). The present study data is represented in a linear model, using input variables of height (Ht), body mass (M), percent body fat (BF), walking speed (S), grade (G), external load carried (L), air temperature (Ta), and relative humidity (RH). The current model provided accurate results (R = 0.98, R^2 = 0.97, adjusted R^2 = 0.93) and is described in Table 3.

Table 3. Linear model for predicting metabolic cost of locomotion while carrying external load.

Model Parameter	Coefficient
Intercept	251.77
Air Temperature (Ta, °C)	0.776
Body Fat (BF, %)	-0.011
Body Mass (M, kg)	2.312
External Load (L, kg)	15.695
Grade (G, %)	29.612
Height (Ht, cm)	-0.138
Relative Humidity (RH, %)	-0.266
Speed (S, $m \cdot s^{-1}$)	338.392

Another important practical consideration is the effects of grade and terrain surface properties on energy costs during locomotion. A significant shortcoming in the ACSM [4] model is the inability to account for terrain types. By design, the ACSM model [4] is flawed with the inability to properly calculate energy costs over negative grades; while this seems to be a flaw for the Pandolf et al., [6] also, it should be noted that a correction factor specific for downhill grades was later developed [13]. The equations from both Givoni and Goldman [5] and Pandolf et al., [6] have a provision for incorporating terrain surface conditions into their equations. Pandolf et al., [6] has one of the more recognized and widely used set of characteristics with inputs for various terrains (η). A recent assessment from Richmond et al., [14] used more comprehensive methods combining physiology, biomechanics, soil sciences, physics, and engineering methods. However, for this treadmill based study, there is no terrain surface effect. Therefore, the specific effect of terrain surface properties could not be assessed.

DISCLAIMER

The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in DOD Instruction 3216.02 and the research was conducted in adherence with the provisions of 32 CFR Part 219. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to DoD Instruction 3216.02 and 32 CFR 219 on the use of volunteers in research. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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