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PREDICTING ENERGY EXPENDITURE WITH LOADS WHILE STANDING OR WALKING VERY SLOWLY

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Previously we presented a formula to predict metabolic rate (M) for walking and load carrying; it could not be used for walking speeds below 0.7 m/s (2.5 km/hr). Six men each carried loads of 32, 40 and 50 kg while walking at 1.0, 0.8, 0.6, 0.4 and 0.2 m/s, to extend the range of speed down to the standstill level. Metabolic cost of standing with 0, 10, 30 or 50 kg backpacks was also investigated in 10 men to evaluate the energy expenditure of →

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load carriage while standing. Energy expenditure increased with external load, both standing and walking. No increased inefficiency occurred with very slow walking; M decreased smoothly as speed approached zero. The revised predictive formula, empirically derived, which now covers standing and the whole range of walking speeds, ~~has the form:~~ is presented

$$M = 1.5W + 2.0(W + L)\ (L/W)^2 + \eta\ (W + L)\ [1.5V^2 + 0.35VG]$$

where: M = metabolic rate, watt; W = subject weight, kg; L = load carried, kg; V = speed of walking, m/s; G = grade, %; η = terrain factor (η = 1.0 for treadmill). The new formula not only extends the range of application but also allows an adjustment for load as a function of body weight and permits easier calculation of energy expenditure.

Predicting energy expenditure with loads while standing or walking very slowly

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PANDOLF, K. B., B. GIVONI, AND R. F. GOLDMAN. *Predicting energy expenditure with loads while standing or walking very slowly*. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 43(4): 577–581, 1977.—Previously we presented a formula to predict metabolic rate (M) for walking and load carrying; it could not be used for walking speeds below 0.7 $m \cdot s^{-1}$ (2.5 $km \cdot h^{-1}$). In this study, six men each carried backpack loads of 32, 40 and 50 kg while walking at 1.0, 0.8, 0.6, 0.4, and 0.2 $m \cdot s^{-1}$, to extend the range of speed down to the standstill level. Metabolic cost of standing with 0-, 10-, 30-, or 50-kg backpacks was also investigated in 10 men to evaluate the energy expenditure of load carriage while standing. Energy expenditure increased with external load, both standing and walking. No increased inefficiency occurred with very slow walking; M decreased smoothly as speed approached zero. The revised predictive formula which now covers standing and the whole range of walking speeds, has the form

$$M = 1.5W + 2.0(W + L)(L/W)^2 + \eta(W + L)[1.5V^2 + 0.35VG]$$

where M = metabolic rate, watts; W = subject weight, kg; L = load carried, kg; V = speed of walking, $m \cdot s^{-1}$; G = grade, %; η = terrain factor (η = 1.0 for treadmill). The new formula not only extends the range of application but also allows an adjustment for load as a function of body weight and permits easier calculation of energy expenditure.

work; load carriage; human efficiency; surface effects

PREVIOUS WORK at this Institute led to a formula to predict the energy expenditure of walking, taking into account body weight (W), external load carried (L), walking speed (V), the nature of the terrain (η), and the walking grade (G) in percent (11). The applicability and precision of this formula was evaluated for a variety of natural terrains (19) and compared against measured energy expenditure values in the literature (3, 7, 13). As originally developed, the formula had a lower limit of walking speed of 0.7 $m \cdot s^{-1}$ (2.5 $km \cdot h^{-1} \approx 1.5$ mph). This limit is seldom reached while an individual is walking under normal conditions, but during a study for developing terrain coefficients for deep snow with a load (16), subjects became exhausted in less than 15 min while walking at even slower speeds. Additionally, the question of the cost of simply standing with a load had not, to our knowledge, been addressed. It seemed appropriate to investigate whether the zero intercept of the prediction equation for energy expenditure walking (i.e., standing still), as a function of total body weight, was simply an extension of the prediction curve for slow speed walking or, in fact, had to be adjusted for the dynamics of moving the load. Accordingly, studies of walking at very slow speeds and of standing with backpack loads were carried out and a new formula was developed which included the total range of walking speeds from standing.

METHODS

A study was conducted in which six fit, adult male subjects walked for 15 min with each of 15 speed/load combinations. These subjects had an average age (mean ± SE) of 20.0 ± 0.8 yr; height, 175.0 ± 1.9 cm; weight (nude), 78.2 + 1.6 kg; and body fat, 18.0 ± 1.2% determined by the method of Durnin and Womersley (8). The external backpack loads were 32, 40, and 50 kg while the walking speeds were 0.2, 0.4, 0.6, 0.8, and 1.0 $m \cdot s^{-1}$. After walking for 5 min, the subjects were assumed to be in a steady state and three 2-min expired air samples were collected in Douglas bags, from the 5–7th, 9–11th, and 13–15th min. The subjects' stride lengths were not regulated. The experimenter pushed a cart ahead of the subject; the cart held a metronome and the Douglas bags. Distance interval markings were taped on the floor so that the pacer (experimenter) could maintain the specified speed nearly constant by keeping pace with the calibrated metronome.

In a second study, 10 different male subjects were asked to stand for 20 min on 4 different occasions to determine the energy expenditure of standing with 0-, 10-, 30-, and 50-kg external backpack loads. These subjects had an average age (mean ± SE) of 29.1 ± 3.0 yr; height, 176.5 ± 1.8 cm; weight (nude), 78.4 ± 3.8 kg; and body fat, 19.0 ± 2.1% (8). The order of load presentation was randomized for each subject. Three 3-min expired air samples were collected, from the 5–8th, 11–14th, and 17–20th min. Two technicians were available to lift the various external backpack loads onto each subject's back while he remained in the standing position. Because of the amount of weight carried, foam rubber padding was placed under the shoulder straps of the backpack and between the backpack and small of the back to alleviate some of the discomfort.

In both studies, the O_2 and CO_2 concentrations were analyzed with Beckman E_2 and LB-1 analyzers, respectively. Periodically, expired air samples were checked by micro-Scholander analyses. Expired air volume was measured in a Collins Chain Compensated Gasometer.

Energy expenditure was calculated by the method of Weir (20). Since there proved to be no statistically significant differences between the three expired air samples within each test condition, values were accepted as steady state and the average energy expenditure used for a given test condition for each subject.

RESULTS

Table 1 illustrates the mean energy expenditure in $W \cdot kg^{-1}$ (body weight + load) of the six subjects for all three external loads at each of the slow walking speeds. The differences between loads barely reach a statistically significant level ($P < 0.06$) but the differences between speeds are all statistically significant ($P < 0.05$). This differs from our findings at higher velocities where the energy cost, when expressed as $W \cdot kg^{-1}$, is independent of weight (10, 11). Table 2 displays the mean total energy expenditure, in watts, for standing with each external load. The differences between loads are statistically significant ($P < .01$) except between no load and the 10-kg condition.

Formula of the new model. The data from these studies of the energy expenditure of slow walking and standing have been incorporated into an equation along with energy expenditure values from earlier studies at higher walking speeds (10, 12, 18). Most of the assumptions concerning body weight, external load, speed, and grade relationships utilized in the previous prediction formula (11) were used in the new model. The theoretical model from which the new predictive formula has been developed consists of four components.

1) A metabolic cost for standing without load (M_1); this is proportional to the weight of the body and is calculated as 1.5 watts per kilogram of body weight ($M_1 = 1.5W$).

2) A metabolic cost of load bearing while standing (M_2); this is affected by the total weight (subject + load) and is fitted as a function of the load to weight ratio squared ($M_2 = 2.0\,(W + L)\,(L/W)^2$).

3) A metabolic cost for walking on the level (M_3); this is related to a specific terrain (η), considers total weight moved, and is a function of the speed squared ($M_3 = \eta\,(W + L)\,(1.5V^2)$).

TABLE 1. *Mean energy expenditure for slow walking with all three external loads*

	Speed, $m \cdot s^{-1}$				
	0.2	0.4	0.6	0.8	1.0
Energy expenditure, $W \cdot kg^{-1}$	2.15 ±0.06	2.57 ±0.06	2.93 ±0.07	3.38 ±0.08	3.97 ±0.13

Values are means ± SE; kg = body weight + external load.

TABLE 2. *Mean energy expenditure for standing with three external loads*

	No load	External Load		
		10 kg	20 kg	30 kg
Energy expenditure, W	105.6 ±6.2	108.8 ±6.4	124.2 ±4.5	144.3 ±7.5

Values are means ± SE.

4) A metabolic cost for climbing a grade (M_4); this again considers a specific terrain (η) and total weight, and is a linear function of the speed and grade ($M_4 = \eta(W + L)\,(0.35VG)$). However, this component needs further validation at speeds less than $0.7\ m \cdot s^{-1}$.

Thus, the analysis of the studies cited above which considered these four components, led to the revised prediction formula

$$M = 1.5W + 2.0(W + L)\,(L/W)^2 + \eta(W + L)\,[1.5V^2 + 0.35VG]$$

where M = metabolic rate, watts; W = subject weight, kg; L = external load, kg; V = speed of walking, $m \cdot s^{-1}$; G = grade (slope), %; and η = terrain coefficient (η = 1.0 for treadmill. The prediction from this formula can be compared to the previous formula (11) and comparisons made with previously measured energy expenditure values.

Since the old energy expenditure prediction formula (11) was compared to experimental studies of many different investigators (2, 3, 6, 7, 10, 13, 17, 21), using different subjects walking at different speeds, grades and carrying different loads, it seems appropriate to compare the new formula to the old one. Figure 1 compares the new and old formulas for predicted energy expenditure (M) at various walking speeds (V) and grades (G), for a 70-kg individual carrying no load while walking on a treadmill. Differences in energy expenditure between formulas at equivalent grades are very small, with the greatest differences being at the higher grades (i.e., 16 and 24%). Also, there is some deviation between formulas near the lower predictive limit ($0.7\ m \cdot s^{-1}$) of the old formula.

Figure 2 compares these two predictive formulas for the same individual carrying a 30-kg external load. Differences in predicted energy expenditure between formulas are even smaller than in Fig. 1. The importance of external load carried (L) is illustrated by the elevated intercept (standing energy expenditure) associated with the external load carried. This intercept can be compared with the intercept displayed in Fig. 1 and can be accounted for by the M_2 component of the new formula.

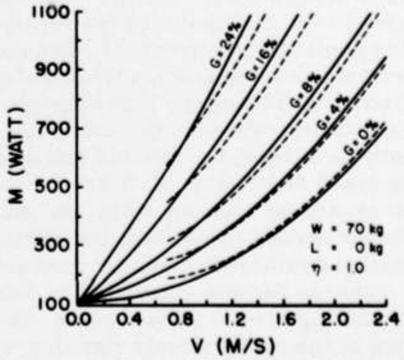

FIG. 1. Comparison of new (*solid line*) and old (*dashed line*) (11) prediction formulas for energy expenditure of an individual weighing 70 kg, while walking carrying no external load and considering the entire range of walking speeds and various grade elevations.

Figure 3 displays a direct comparison of predicted energy expenditure for walking at various grades, for an individual weighing 70 kg but carrying an external load of 40 kg compared to no external load. Notice the difference between intercepts (standing) for these different external load conditions. This difference can again be accounted for by the M_2 component of the new formula; the actual energy expenditure curve conformations are derived primarily from the M_3 and M_4 components of the new predictive formula. It is interesting to note the nearly equivalent energy expenditures for walking up an 8% grade carrying 40 kg and carrying no load up a 16% grade.

The validity of the new predictive formula was checked by comparing the predicted with the measured energy expenditures in the study of Goldman and Iampietro (10). The walking speed (0.7–1.8 $m \cdot s^{-1}$), load carried (10–30 kg), and percent grade (3–9%) offered a wide range of energy expenditure values. The correlation coefficient (r) between the predicted and measured values is presented in Fig. 4. This coefficient ($r = 0.96$) is identical to that calculated and presented from the old formula (11).

The type of surface is known to affect the measured energy expenditures. Previously, a variety of terrain coefficients were derived to allow for more accurate prediction of energy expenditure considering the walking surface (16, 19). Single coefficients were found to fit all measured values except for soft snow. The coefficient for soft snow was found to increase as the snow footprint depth increased ($\eta = 1.3 + 0.08$ *cm depression*). Predicted energy expenditure (M) as a function of walking speed (V) for various level terrains is illustrated in Fig. 5. Whereas firm walking surfaces appear to alter the terrain coefficients only slightly ($\eta = 1.0$–1.5), surfaces which allow penetration (i.e., swamp bog, loose sand, and soft snow of different depths) alter the coefficients much more dramatically. Walking on loose sand ($\eta = 2.1$) is twice as costly (metabolically) as on a blacktop surface or treadmill, while traversing soft snow with a footprint depth of 35 cm is approximately four times more demanding compared to blacktop or treadmill.

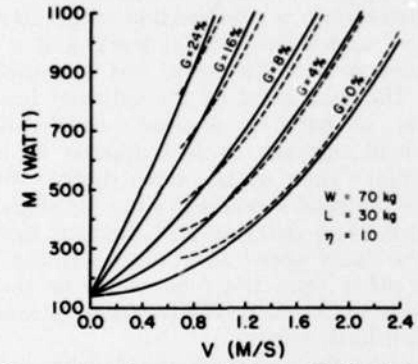

FIG. 2. Comparison of new (*solid line*) and old (*dashed line*) (11) prediction formulas for energy expenditure of an individual (70 kg), while walking carrying a 30-kg external load, at various grades throughout the entire range of walking speeds.

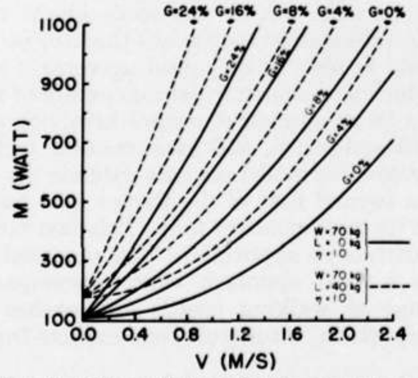

FIG. 3. New formula predictions for the energy expenditure of walking comparing an individual weighing 70 kg, carrying either no load or a 40-kg external load from standing through the entire range of walking speeds and at various grades.

DISCUSSION

The energy expenditure of walking may vary within wide individual limits and also vary for a given individual depending on a number of factors. It certainly depends on total weight (body weight and external load), walking speed, type of surface, and grade (1, 11). Ideally, prediction of energy expenditure should encompass the entire range of walking speeds from standing. The upper limit for walking speed has been shown to be approximately 8.5 $km \cdot h^{-1}$ (≈ 2.4 $m \cdot s^{-1}$); at greater walking speeds, the efficiency of walking becomes lower than running (14, 15). Obviously, such individuals as champion race walkers would display a higher upper limit for walking speed (23).

The lower limit for walking (0.7 $m \cdot s^{-1}$) of the old predictive formula (11) was taken because of a lack of available predictive data below that point and recogni-

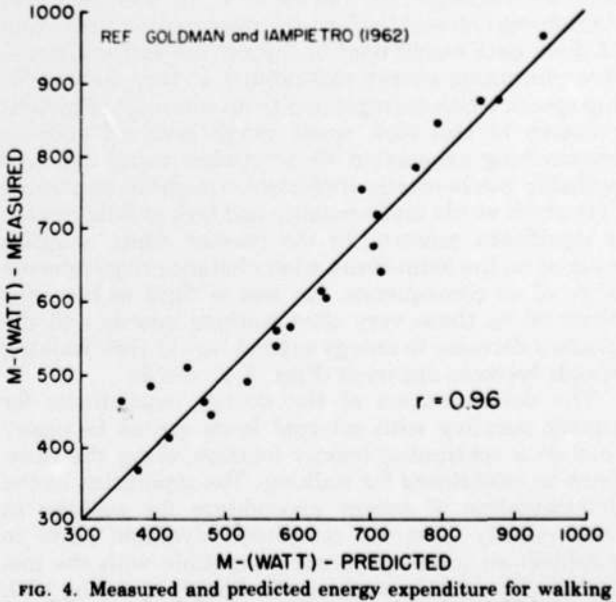

FIG. 4. Measured and predicted energy expenditure for walking at various speeds (0.7–1.8 $m \cdot s^{-1}$), external loads (10–30 kg), and grade elevations (3–9%). Reference is to work by Goldman and Iampietro (10).

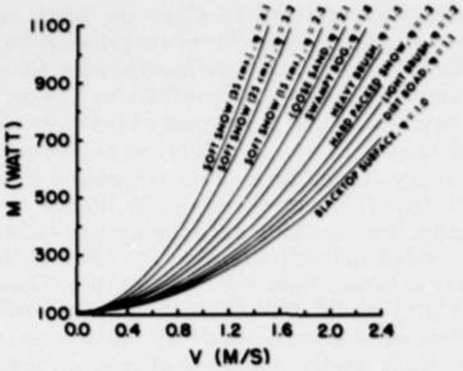

FIG. 5. Predicted energy expenditure for walking at various speeds considering the type of terrain.

tion of three possible alternatives for energy expenditure while walking at such slow speeds: *1*) the energy expenditure of walking at slower speeds ($<0.7\ \mathrm{m \cdot s^{-1}}$) would rise steadily because of increasing inefficiency and lack of fluid motion, forming a parabolic function following the original curve described in our old prediction formula (11) and hypothesized earlier by Cathcart et al. (4); *2*) the energy expenditure of walking somewhat more slowly than $0.7\ \mathrm{m \cdot s^{-1}}$ (i.e., $\sim 0.5\ \mathrm{m \cdot s^{-1}}$) would be equivalent or higher than walking at $0.7\ \mathrm{m \cdot s^{-1}}$, but as speed approached zero the expenditure would fall at some breakpoint (this seemed more logical than the concept of a continually increasing energy expenditure with decreasing speed, and finds some support in the literature (14, 15)); *3*) despite the suggestions in the literature, there was a possibility that the expenditure of walking at speeds less than $0.7\ \mathrm{m \cdot s^{-1}}$ would continue to decrease.

Although measured values were collected to a lower limit for walking of 0.5 and $0.6\ \mathrm{m \cdot s^{-1}}$ by Workman and Armstrong (22) and Bobbert (3), respectively, inspection of these data would tend to support the latter alternative concerning energy expenditure at very slow walking speeds when extrapolated to an intercept. Previous research in this slow speed range involved subjects approaching exhaustion (9) or studies using old (and probably mechanically inefficient) treadmill apparatus (14) which would make balance and lack of fluid motion a significant concern. In the present study, subjects walked on linoleum floors where balance requirements were of no consequence. No loss of fluid motion was observed at these very slow walking speeds and the gradual decrease in energy expenditure at slow walking speeds becomes apparent (Figs. 1, 2, and 3).

The determination of the energy expenditure for simply standing with external loads cannot be examined as a continuing energy function along the same lines as established for walking. The separation in the determination of energy expenditure for walking at zero velocity from its component dynamic parts to establish an intercept is not compatible with the mechanics involved in walking (5). Simply standing with packs constitutes an entirely different work mode, static work, which involves primarily tension in muscles utilized for maintenance of the load. By physical laws, no mechanical work is done as in walking and, therefore, it cannot be related, in that sense, in physical terms. However, the development of tension does require energy (1). Thus, in standing the speed is zero, but the mechanical components which play a role in the cost of walking are lacking. Therefore, in the new predictive formula the energy expenditure for simply standing (static work), with or without load, is expressed by the first two terms (M_1 and M_2) and is developed by the remaining components (M_3 and M_4) for dynamic movement.

Based on the findings of the present study at slow walking speeds, we have for the first time shown an energy expenditure difference for various loads carried which remained significant ($P < 0.06$) when expressed as expenditure per kilogram. We believe this is a result of the M_2 component, which expresses the energy expenditures of a load in relationship to the body weight of the bearer. The contribution of this term would be apparent for standing or walking at very slow speeds, but appears to have been masked at the higher velocities studied.

The added energy expenditure involved in walking over different terrains has been illustrated (Fig. 5). Obviously, the greater the penetration allowed by the terrain the higher the energy demands. These terrains seem to necessitate a combination of greater muscle mass usage, added lift (static) work and a forward stooping posture with the associated increased energy demands. The placement of the external load (head, hands, feet, or back) is another consideration. For example, load carriage by foot appears to be about fivefold greater than by the torso (back), while load carriage on the head appears to cost only slightly more per kilogram than carrying the identical load on the torso at the same speed (18). Consideration for load placement other than the torso must be revalidated however, since the new predictive formula was derived for backpack loads only.

In conclusion, the new predictive formula shows good agreement between measured and predicted values (Fig. 4). It allows prediction for slow walking down to standing, with consideration for load carriage, terrain and grade. However, the M_4 component of the new predictive formula which considers grade climbing needs to be validated at speeds less than $0.7\ \mathrm{m \cdot s^{-1}}$. The new formula is also in very good agreement with the old one, which was shown to provide excellent fit to the results of a large number of studies involving different subjects, investigators, and experimental techniques. The new predictive model not only extends the range of application beyond that of the former one, but also is simpler in its mathematical form. This last factor may greatly facilitate its application. This proposed formula represents a final approach which encompasses the entire range of walking speeds and evokes the V^2 relationship which, intuitively, one expects from physics.

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