Potter, AW, Santee, WR, Clements, CM, Brooks, KA, & Hoyt, RW. Comparative analysis of metabolic cost equations: A review. J Sport Human Perf 2013;1(3): 34-42
doi: 10.12922/jshp.0009.2013

JOURNAL OF SPORT AND HUMAN PERFORMANCE

REVIEW OPEN ACCESS

COMPARATIVE ANALYSIS OF METABOLIC COST EQUATIONS: A REVIEW

Potter, AW[1], Santee, WR[1], Clements, CM[1], Brooks, KA[2], & Hoyt, RW[1]

U.S. Army Research Institute of Environmental Medicine, Natick, MA[1]

Texas A&M University Corpus Christi, Corpus Christi, TX[2]

ABSTRACT

Military personnel often engage in multi-day missions in harsh environments that require physical strength and endurance. Predicting the metabolic costs of dismounted military movements is of critical importance for mission planning and ensuring Soldier safety. The ability to accurately predict individualized thermo-physiological responses specific to variables such as clothing, equipment, weather, terrain, and environment is of significant concern. While there are multiple equations published that predict metabolic cost, only a few account for all of these variables. This paper compares several well-recognized equations that address the needs of the military: 1) Givoni & Goldman (1971), 2) Pandolf et al. (1977), 3) American College of Sports Medicine (ACSM) (2000), 4) Minetti et al. (2002), and 5) Santee et al. (2003b). This review shows that existing equations generally lack some of the required elements for estimating military activities and, with the exception of the Pandolf Equation, others do not account for an external load, resting conditions and terrain or surface characteristics. Furthermore, this review outlines the need for continued refinement of existing equations or development of improved estimation equations.

Keywords: energy expenditure; exercise; locomotion; predictive equation; modeling

INTRODUCTION

In our modern-day military, dismounted Soldiers, Marines, Sailors, and Airmen routinely face high mental and physical demands while engaging in training exercises and actual operations in harsh environments. Physical demands during training and deployments among dismounted military personnel are commonly driven by the need to carry loads of 35 to 65 kg or more for protracted periods (3). These heavy loads increase the risk of hyperthermia, hypo-hydration, under-nutrition, and degraded mental and physical work capacities (8).

To help manage these risks, soldiers commonly rely on guidance such as Technical Bulletin Medicine (TB MED 507) (18) or Foot Marches Field Manual (FM 21-18) (5), and mission planning aids such as the Heat Strain Decision Aid (2) or SCENARIO (9). Mathematical algorithms that predict the metabolic cost of various physical activities are at the heart of these mission planning tools. Estimates of metabolic energy expenditure, and knowledge of individual characteristics (gender, age, height, weight, body fat, fitness) and clothing and equipment properties (e.g., insulation, water vapor permeability, weight), enable prediction of metabolic heat production, body temperatures, work intensity, metabolic fuel requirements, and water requirements. The purpose of the present paper is to review the characteristics and validity of select algorithms for estimating the metabolic energy expenditures of foot soldiers.

Metabolic cost estimates can be used as a quantitative tool for assessing the performance potential of soldiers to predict the physiological response of individuals engaged in military operations, including dismounted movements. These predictions can be used for mission planning and safety assessments (e.g., establish work-rest cycles, water requirements, etc.), if accurate predictions of metabolic cost are available. In addition, quantifying mission specific variables such as clothing and equipment worn, weather conditions, and terrain factors, also play critical roles in making more precise estimations of physiological status.

The adverse impact of heavy loads on the ability of foot soldiers to move and accomplish their missions is well documented in historical accounts and continues to be relevant in modern-day military operations (8). Prolonged load carriage combines elements of both strength and endurance aerobic exercise capacity.

Although athletes and military personnel both engage in strenuous physical activity, significant differences exist between the two populations. Athletes commonly specialize in strength or endurance, e.g., weight lifting or long distance running. These activities have a marked effect on body composition and physiology as shown by Keul (7). Soldiers need to develop an efficient middle-ground between these two extremes. Soldiers need both the muscle mass needed to carry heavy loads and the aerobic capacity in order to sustain high physical work demands.

Research by Keul (7) showed that training effects of focusing on solely endurance or weight-lifting has a significant effect on the physiological responses of individuals. This is evident in both performance of given tasks (e.g., endurance, lifting strength, etc.) and in the physiological recovery after or between tasks (i.e., heart rate recovery, blood flow, etc.) (7). Generally, with the possible exception wife-carrying (10), most sports do not place heavy external loads on the body during sustained locomotion; whereas virtually all dismounted tactical movements require some load carriage where the burden includes clothing ensembles and specialized equipment. For soldiers, exercise duration is typically much longer than that seen in athletic events (e.g., days versus hours) and the work intensity (% VO_2max) is less (e.g., <50% versus 60-80% or more). This contrast in absolute workload over time can be seen as the daily energy expenditure has been shown to be similar between military and athletes; while the extended duration plays a significant role in the overall physiological decrement (19).

Goals and Objectives

The goals of this brief review are to (a) compare frequently cited equations for estimating the metabolic cost of locomotion with and without load carriage, (b) discuss the value of these predictive equations to sports medicine, occupational medicine, military operational medicine, and to obesity and diabetes research, and (c) review the limitations of these equations, and discuss future research directions.

The ability to accurately estimate work rate (metabolic energy expenditure), when combined with a knowledge or estimate of individual aerobic fitness (VO_2max), body characteristics (gender, ht, wt, % body fat), antecedent diet, clothing biophysics (insulation, water vapor permeability), and local weather, permits estimation of metabolic energy expenditure and heat production, work intensity (%VO_2max or % of maximal aerobic capacity), metabolic fuel use (energy and carbohydrate/fat), heat storage, and water requirements. The ability to holistically model and predict these aspects of human physiology has broad scientific and medical relevance.

Methods and Approach

A literature review was conducted to identify extant metabolic cost prediction equations. The next step was a down-selection based on required input variables (speed, grade, and mass), citations, and "uniqueness".

Selected Equations

1. Givoni & Goldman (1971)
2. Pandolf et al. (1977) and Downhill Correction Factor (Santee et al., 2003a)
3. American College of Sports Medicine (ACSM) (2000)
4. Minetti et al. (2002)
5. Santee et al. (2003b)

1. Equations from Givoni & Goldman (1971)

The equation from Givoni and Goldman (6) was empirically derived using data from a mixed sample of male and female test volunteers from three separate sets of unpublished data. Study #1 included 12 male subjects; study #2 included 6 female subjects; and study #3 included 8 male subjects. Development of this equation was done using a mixture of varied speed, grade, and of loaded and unloaded individuals.

$$M_W = \eta \bullet (W+L) \bullet [2.3 + 0.32 \bullet (V-2.5)^{1.65} + G \bullet (0.2 + 0.07 \bullet (V - 2.5))]$$

Where M_w = metabolic cost of walking (in watts); η = terrain factor (terrain for this equation was only considered as 1.0 as it accounted for treadmill surfaces only); W = body mass (kilograms); L = load mass (kilograms); V = velocity or walk rate (kph); and G = slope or grade (%) (6).

2. Pandolf Equation (Pandolf et al., 1977)

The Pandolf Equation, one of the most cited metabolic cost equations, was empirically developed as a refinement of the work of Givoni and Goldman (1971), adding considerations for terrain and for standing (12).

$$M_W = 1.5 \bullet W + 2.0 \bullet (W + L) \bullet (L / W)^2 + \eta \bullet (W + L) \bullet (1.5 \bullet V^2 + 0.35 \bullet V \bullet G)$$

Where Mw = metabolic cost of walking (or standing) (in watts); W = body mass (kilograms); L = load mass (kilograms); ŋ = terrain factor; V = velocity or walk rate (m/s); G = slope or grade (%). The terrain factor categories are: 1.0 = black top road or treadmill; 1.1 = dirt road; 1.2 = light brush; 1.5 = heavy brush; 1.8 = swampy bog; 2.1 = loose sand; 2.5 = soft snow, 15 cm depth; 3.3 = soft snow 25 cm deep; 4.1 = soft snow, 35 cm depth (12).

The Pandolf Equation has two parts, a standing metabolic rate and a moving metabolic rate. When movement velocity is zero (no locomotion), an estimate of the metabolic cost of standing with or without a load is provided (i.e., the second half of the equation is not used). The first section of the Pandolf Equation, i.e., [(M = 1.5W + 2.0(W + L) $\cdot$ (L / W)^2] assumes a 1.5 W/kg metabolic cost of standing without a load and accounts for additional load as a function of individual body weight. The second part of the Pandolf Equation, i.e., [ŋ (W + L) $\cdot$ (1.5V^2 + 0.35VG)], assumes a metabolic cost of walking on level grade (i.e., ŋ = 1) is a function of the total weight of the individual and added velocity squared and accounts for percentage grade, velocity, total weight, and terrain. The data used to develop the Pandolf Equation were collected using military test volunteers. The sample population for constructing and validating the standing metabolic rate (part 1) consisted of 10 male volunteers (age 29.1 ± 3.0; wt 78.4 ± 3.8 kg; % body fat 19.0% ± 2.1; ht 176.5 ± 1.8 cm, $\bar{X}$ ± SD). The sample population for constructing and validating the moving metabolic rate (part 2) consisted of six male volunteers (age 20.0 ± 0.8; wt 78.2 ± 1.6 kg; % body fat 18.0% ± 1.2; ht 175.0 ± 1.9 cm) (12).

The original Pandolf Equation did not adequately account for the metabolic cost of downhill locomotion (14). To address this issue, a Correction Factor (CF) was developed that accounts for the decrease in energy expenditure during downhill walking, i.e., when % grade < 0 (16). This correction factor (CF) is infrequently cited but nevertheless an important improvement to the Pandolf Equation. The CF is:

$$CF = \eta \bullet [(G \bullet (W + L) \bullet V) / 3.5 - ((W + L) \bullet (G + 6)^2) / W) + (25V^2)]$$

Where η = terrain factor; G = grade (%) (e.g., if the grade is −8%, use a value of −8); W = body wt (kg), L = load wt (kg), V = velocity (m/s). Thus, the total metabolic cost (M_T in watts) for downhill walking is the difference between the Pandolf Equation (PE) estimate of the metabolic cost of locomotion and the Correction Factor (CF), i.e., M_T = PE – CF (16).

Another limitation of the Pandolf Equation is that it was designed to predict the response to steady state exercise of less than 30 min durations, rather than predict the effects of intermittent exercise on metabolic cost (i.e., transient work, rest periods, etc.). Also, for prolonged exercise, the Pandolf Equation doesn't account for observed increases in metabolic energy cost (4,13). Epstein et al. (4) and Patton et al. (13) showed that prolonged walking with load at a constant speed resulted in increased energy costs over time. Both studies concluded that if energy expenditure models were used to estimate energy costs over an extended period of time (i.e., 2 hours of more), those costs would be significantly underestimated (~10-16%) (4,13).

3. American College of Sports Medicine (ACSM) (2000)

The American College of Sports Medicine (ACSM) (1) provides equations for estimating oxygen consumption (VO_2) for various activities (walking, running, stepping, and leg and arm ergometry). Each of these equations is based on mechanical work estimations and each shares a similar structure of inputs for VO_2 of horizontal, vertical, and resting components in the standard equation of: VO_2 = H + V + R. Each activity-specific equation uses a regression equation for converting movement velocity in m/min into VO_2 per kilogram of body weight (ml.kg.min^{-1}). Only the walking equation is being considered in this review.

$$VO_2 = H + V + R$$

$$VO_2 = 0.1(\text{speed}) + 1.8(\text{speed}) \cdot (\text{fractional grade}) + 3.5$$

Where VO_2 is O_2 consumption in ml.kg.min^{-1}; velocity (speed) in m/min; and grade is in decimal form for percentage (e.g., 8% = 0.08). Appropriate unit conversions would be needed to make this equation comparable to other typical equation terms (i.e., VO_2max in ml.kg.min^{-1} would need to be converted to watts). However, with the exception of an additional load component, the basic elements remain (i.e., VO_2 would be metabolic cost; horizontal (H) would be forward velocity; weight is a factor within movement elements; vertical (V) would be the grade (incline or decline); and the resting component (R) represents the resting metabolic rate (RMR or BMR) (assumed to be 3.5 ml.kg.min^{-1}).

4. Equations from Minetti et al., (2002)

Work by Minetti and coworkers primarily focused on estimating the metabolic cost of mountain foot races and running, but does include information on walking. The sample population used to develop these equations consisted of 10 male volunteers (age 32.6 ± 7.5; wt 61.2 ± 5.7 kg; VO_2max, 68.9 ± 3.8 ml.kg.min^{-1}). A significant shortcoming of this equation is that the metabolic cost of carrying an added external load is not estimated. In addition, resting metabolic rate (RMR) is not included and must be added in using one of the standard equations for estimating RMR, e.g., Roza and Shizgal (15).

$\grave{E}$ = net metabolic energy expenditure (W/kg) – RMR subtracted for net VO_2

$\hat{W}_{vert} = gv \sin(\arctan|i|)$ [mechanical work rate, W/kg]

$$Cw\ (walk) \rightarrow Cw_i = 280.5i^5 - 58.7i^4 - 76.8i^3 + 51.9i^2 + 19.6i + 2.5$$

Where $\hat{W}_{vert}$ = mechanical efficiency work rate (W/kg); g = gravity (9.81 m/s^2); v = velocity (m/s); i = gradient (0.0 – 0.50); and eff = efficiency). For the variables below, $C_{eff}(1) \approx C_{eff}(2)$

$$C_{eff}(1) = \hat{W}_{vert} \bullet (v*eff)^{-1}$$

$$C_{eff}(2) = g \bullet \sin(\arctan|i|)/eff$$

5. Equations from Santee et al. (2003b)

The equations from Santee et al. (17) are, by design, individual sub-components for the prediction of energy costs. These equations were developed to expand upon and improve the understanding of metabolic cost of locomotion with added load carriage, as well as for movements over positive and negative grades (i.e., uphill and downhill walking) (Table 1). In contrast to the other equations discussed here, the Santee equations were developed to predict the metabolic cost of locomotion over complex terrain and be used as elements of more complex models.

Table 1. Santee et al., (2003b) Component Equations:

Equation	Use
$W_L = 3.28m_t + 71.1$	Level (0%)
$W_{UP} = W_L + 3.5\ (m_t gh/s)$	Uphill (>0%)
$W_{DOWN} = W_L + 2.4\ (m_t gh/s)\ 0.3^{(\alpha/7.65)}$	Downhill (<0%)

Where W_L = metabolic cost of walking at level grade; W_{UP} = metabolic cost of walking uphill (i.e., at positive >0% grade); W_{DOWN} = metabolic cost of walking downhill (i.e., at negative <0% grade); m_t = total mass displacement (including individual body weight, clothing, and load); g = acceleration imposed by gravity (9.8 m/s^{-2}); h = the vertical displacement of 1.34 m/s for each given grade; and α = the angle of each give negative slope. The sample population used to develop these equations consisted of eight male volunteers (age 24.0 ± 4.0; wt 80.2 ± 9.9 kg; % body fat 20.5% ± 4.7; ht 174.0 ± 7.0 cm; VO_2max, 51.6 ± 4.6 $ml.kg.min^{-1}$).

METHODS

In order to compare the equations, uniform input variables were used to neutralize additional load and terrain effects. Also in equations where added load is not exclusively defined, additional load was included in the measure of total mass (i.e., additional weight carried is added to the total mass). Two mathematical comparisons were made using a standard male soldier weighing 70 kg with no additional load, walking at speeds from 1.0 m/s (3.6 kph) to 2 m/s in increments of 0.1 m/s (Figure 1), as well as a comparison using a standard 70 kg male soldier walking at a set foot march speed of 1.55 m/s (3.5 kph), and carrying a 10 to 60 kg load (Figure 2).

RESULTS

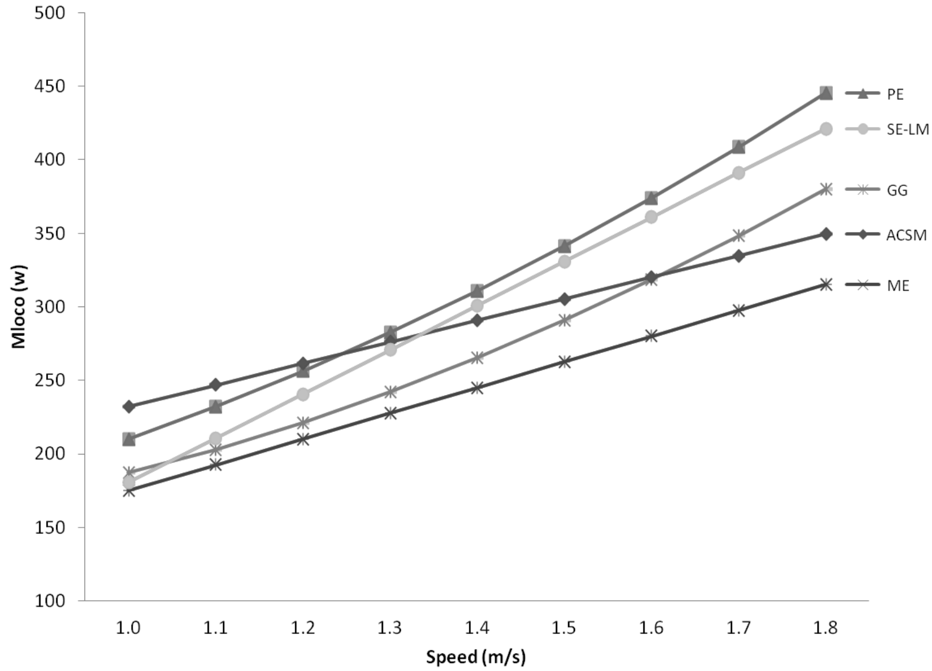
The graphical presentation of figures 1 and 2 show that while differences exist between these methods there remains some consistencies in the shape of the curves. The noticeable difference between the Pandolf Equation compared to the other equations reviewed may be due to differences in the way the metabolic cost of load carriage is estimated. That is, the Pandolf Equation accounts for additional load explicitly while the others do not. Another consideration is the range of study conditions used in the baseline studies. For example, Santee (2003a, 2003b) used external loads up to 27 kg, whereas Givoni and Goldman, and Pandolf et al. (1977) used fixed loads up 55 kg.

DISCUSSION

The complexity and lack of equations for estimating or predicting metabolic energy costs during locomotion and load carriage are not due to a shortage in scientific studies. There are several scientifically valid approaches for determining the metabolic cost/energy expenditure associated with load carriage. Each of the selected methods includes the critical components of speed, grade, and inputs for individual weight. These studies illustrate the difficulty in translating this scientific information into a generally usable equation. Many of the available methods have varying input requirements or omit methods for accounting for additional load, differences in grade effects, resting metabolic rate, and terrain type. We found in our review, even when the equations incorporate the requisite elements, they differ in terms of input requirements, the effect of grade, and all but one of the equations (i.e., Pandolf Equation) have no mechanism to account for an external load, resting conditions and terrain or surface characteristics.

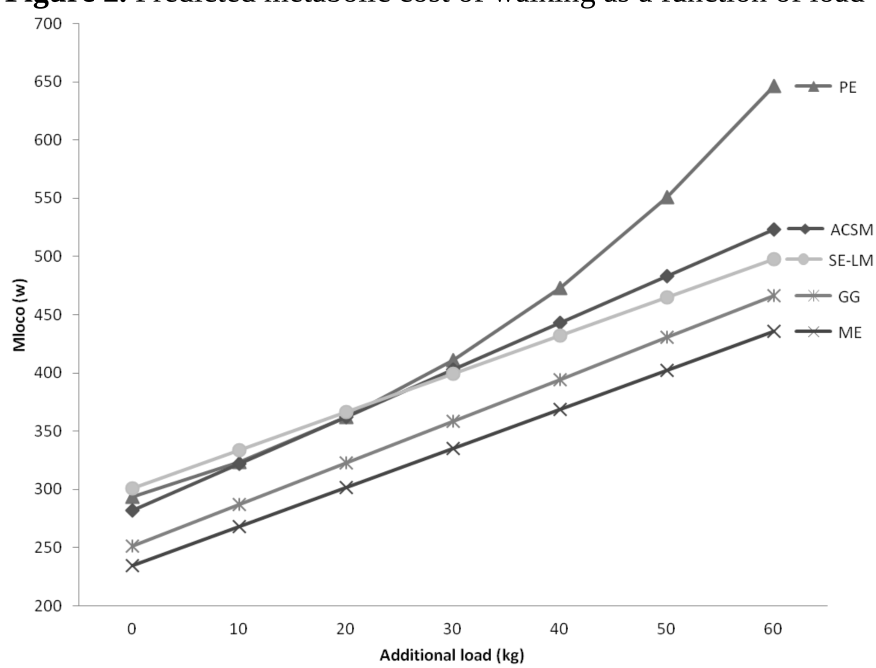
Developing predictive equations that have a potential for real-time applications is of significant importance to the US military. From this perspective, it will be necessary to develop and/or refine these metabolic cost equations or develop new equations to account for a variety of complex conditions. Specific examples of improvements include ways to account for interpersonal effects of rest periods during foot movements, the time effects on VO_2 during sustained movements, estimates of the time to exhaustion, and the metabolic cost of various types of exercise (e.g., lifting or digging).

Figure 1. Predicted metabolic cost of walking as a function of speed



Assuming a 70kg fit male. PE = Pandolf Equation; ME = Minetti Equation; GG = Givoni & Goldman Equation; ACSM = American College of Sports Medicine equation; and SE-LM = Santee Level Equation modified

Figure 2. Predicted metabolic cost of walking as a function of load



Assuming a 70kg fit male walking at a set pace of 1.34 m/s. PE = Pandolf Equation; ME = Minetti Equation; GG = Givoni & Goldman Equation; ACSM = American College of Sports Medicine equation; and SE-LM = Santee Level Equation modified

ISSN: 2326-6333

Disclaimer

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. 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.

REFERENCES

1. American College of Sports Medicine (ACSM). ACSM's guidelines for exercise testing and prescription (6th ed.) Baltimore, MD: Lippincott Williams & Wilkins, 2000.
2. Blanchard, LA, & Santee, WR Comparison of USARIEM heat strain decision aid to mobile decision aid and standard Army guidelines for warm weather training. Technical Report T08-7, U.S. Army Research Institute of Environmental Medicine, 2008.
3. Dean CE. The modern warrior's combat load: dismounted operations in Afghanistan, April-May 2003. Fort Leavenworth, KS. Army Center for Lessons Learned 2004. [Google Scholar]
4. Epstein Y, Rosenblum J, Burnstein R, Sawka MN. External load can alter energy cost of prolonged exercise. European Journal of Applied Physiology 1988;57(2):243-247. PubMed PMID: 3349993. [Google Scholar]
5. FM 21-18. Foot marches, Department of the Army. Washington, D.C., 1990.
6. Givoni B, Goldman RF. Predicting metabolic energy cost. Journal of Applied Physiology 1971;30(3):429-433. PubMed PMID: 5544128. [Google Scholar]
7. Keul J. The relationship between circulation and metabolism during exercise. Medicine and Science in Sports 1973;5(4):209-219. PubMed PMID: 4590141. [Google Scholar]
8. Knapik, J. & Reynolds, K. Load carriage in military operations: a review of historical, physiological, and medical aspects. Santee, W.R. and K.E. Friedl (eds), Borden Institute Monograph Series, US Army Medical Research and Material Command, Ft. Detrick, MD, 2010.
9. Kraning KK, Gonzalez RR. A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration. Journal of thermal biology 1997;22(4):331-342. [Google Scholar]
10. Lee IM, Titze S, Oja P. Wife carrying for health. Med J Aust 2011;195(11):723-725. [Google Scholar]
11. Minetti AE, Moia C, Roi GS, Susta D, Ferretti G. Energy cost of walking and running at extreme uphill and downhill slopes. Journal of Applied Physiology 2002;93(3):3-1039. Available from: http://jap.physiology.org/cgi/pmidlookup?view=long&pmid=12183501 PubMed PMID: 12183501. doi: 10.1152/japplphysiol.01177.2001. [Google Scholar]

12. Pandolf KB, Givoni B, Goldman RF. Predicting energy expenditure with loads while standing or walking very slowly. Journal of Applied Physiology 1977;43(4):577-581. PubMed PMID: 908672. [Google Scholar]

13. Patton JF, Kaszuba J, Mello RP, Reynolds KL. Physiological responses to prolonged treadmill walking with external loads. European Journal of Applied Physiology 1991;63(2):89-93. Available from: http://www.nlm.nih.gov/medlineplus/exerciseandphysicalfitness.html PubMed PMID: 1748110. [Google Scholar]

14. Pinmental NA, Pandolf KB. Energy expenditure while standing or walking slowly uphill or downhill with loads. Ergonomics 1979;22(8):963-973. [Google Scholar]

15. Roza AM, Shizgal HM. The Harris-Benedict equation reevaluated: Resting energy requirements and the body cell mass. The American Journal of Clinical Nutrition 1984;40(1):168-182. Available from: http://www.ajcn.org/cgi/pmidlookup?view=long&pmid=6741850 PubMed PMID: 6741850. [Google Scholar]

16. Santee, WR, Blanchard, LA, Speckman, KL, Gonzalez, JA, & Wallace, RF. Load carriage model development and testing with field data. Technical note TN03-3, U.S. Army Research Institute of Environmental Medicine, 2003.

17. Santee WR, Small MG, Blanchard LA. Application of energy cost algorithms for load carriage to field data. Journal of the Human-Environmental System 2003;6(2):69-76. [Google Scholar]

18. TB MED 507. Heat stress control and heat casualty management. Department of the Army, Technical Bulletin Medicine 2003. [Google Scholar]

19. Tharion WJ, Lieberman HR, Montain SJ, Young AJ, Baker-Fulco CJ, DeLany JP, et al. Energy requirements of military personnel. Appetite 2005;44(1):47-65. Available from: http://www.nlm.nih.gov/medlineplus/exerciseandphysicalfitness.html PubMed PMID: 15604033. doi: 10.1016/j.appet.2003.11.010. [Google Scholar]