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TERRAIN FACTORS FOR PREDICTING WALKING AND LOAD CARRIAGE ENERGY COSTS: REVIEW AND REFINEMENT

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ABSTRACT

The ability to predict the energy cost of load carriage is important to various disciplines and applications including anthropology, exercise physiology, humanitarian aid, and dismounted military operations. Energy consumption in turn determines the physiological status of individuals and populations and their ability to function via internal heat production, hydration, fatigue, and caloric intake. Various parameters of the physical environment, including topographic relief and surface conditions impact those energy costs. To be comprehensive, predictive load carriage cost models must incorporate body mass, load, positive and negative grades, and adjustments for surface conditions. Models developed at the U.S. Army Research Institute of Environmental Medicine (USARIEM) in the 1970s incorporated an adjustment for surface conditions, i.e. a terrain factor. However, the terrain factors were derived empirically from data for a relatively limited set of surface conditions or classes. Aside from efforts to apply the classification of terrain factors to a broader set of conditions, little work has been done on to improve terrain factors since the 1970s. This paper reviews the effect of terrain properties on locomotion, the development of terrain factors, and provides scientific improvements based on terrain characterization used in studies of vehicular trafficability at the U.S. Army Engineer Research and Development Center (ERDC).

Keywords: metabolic cost, modeling, military, terrain

INTRODUCTION

The primary purpose of this paper is to review, evaluate and suggest improvements to the terrain factor (η) used in the prediction of energy costs of dismounted movements and load carriage over various surface conditions. As η is meaningful only in the context of energy costs predictive models, a brief review of the walking and load carriage models developed at the U.S. Army Research Institute of Environmental Medicine

(USARIEM) is included in this introduction. Also included is the definition of terrain relative to human energetics before examination of the concept of a terrain factor, η, in depth.

One of the most basic characteristics of an individual or a population is energy utilization. Human performance and survival, can be defined by availability of energy, how it can be utilized to engage in activities, and how heat by-products impact homeostasis. Therefore an energetics approach is useful for systematic evaluation and development of models describing and predicting physiological status and activities of individuals or a population on a time scale from near-real-time to entire life cycles.

This paper addresses the energy costs of walking, load carriage, and to a limited extent, resting metabolic costs. A more comprehensive energetics approach would require a full range of values describing resting to strenuous activities. Thus the focus of this paper is on individuals where a significant portion of their time budget is dedicated to movement between locations and transport of loads.

Energetics

Almost all human performance is limited by the availability of energy and/or its by-products such as metabolic heat production. These are typically modeled using energy balance and heat balance equations. Although these concepts are sometime used interchangeably, an energy balance is often associated with total or gross energy intake or flow, such as the between trophic levels in an eco-system or the daily energy budget of an individual or population (Joules (J) or kcals). In contrast, heat balance equations for biological systems are primarily physiological constructs, starting with the release of energy by metabolism or other biological mechanisms, and the consumption of energy to maintain physiological functions or perform activities. Heat balance equations are often presented in units for the rate of energy consumption (Js^{-1}, W, kcal/h) or as an energy flux (W/m^2) relative to body surface area.

Internal heat production is a by-product of metabolism and muscle activity, while exposure to weather related environmental extremes, such as high or low air temperature, wind and solar radiation also impact the thermal state of individuals. Under these relatively primitive or basic conditions, the cost of locomotion, especially if significant loads and/or distances are part of the scenario, is an important contributor to the energy and heat budgets. In more primitive cultural situations, such as hunter-gather societies and refugee camps, the activities may be the basic functions of foraging for food, and the collection and transport of water and firewood. Anthropologists and archeologists use both energy and heat balance as tools to describe primitive cultures and to determined requirements for humanitarian aid.

Given the importance of locomotion, and especially load carriage, during activities that involve significant non-mechanized cross-country movement, it is of value to measure, and ultimately to predict, the cost of those activities. A significant amount of the research in human performance has been devoted to the energetics of competitive sports, but most of those activities take place under very controlled physical environmental conditions. While the basic elements are similar, sports medicine does not generally address the complexity or heterogeneity of the physical environment. One collective term for the natural physical structure features of an outdoor locality or landscape is terrain.

Terrain

Terrain is the physical or structural features of the environment which individuals or population may occupy, move over, or through within a defined time or space. Terrain properties include topographic relief (i.e., changes in relative elevation), whether extremely homogenous (e.g., a salt flat) or extremely diverse (e.g., a boulder field), or abrupt (e.g., a cliff face). Terrain features include cliffs and other physical features or obstacles (e.g., bodies of water and topography) that may impede movement, or trails and roads that may enhance movement. Urban terrain may include buildings or ruins. One important terrain feature, whether discussing vehicular or dismounted (foot) movement is the physical characteristics of the surface being walked or driven over. In most athletic competitions, a concerted effort is made to make the surfaces relatively homogeneous, such as a running track or football fields.

Terrain effects on locomotion

This paper examines terrain parameters, with respect to how they influence human movement. The information presented is primarily based on the physics-based knowledge of vehicle movement over terrain, developed at the U.S. Army Engineer Research and Development Laboratory (ERDC).

In general, as a human walks over terrain, several parameters can be identified that affect how fast or how much energy it takes to walk on the terrain surface:

- **Sinkage** – how deep a foot will sink (into the terrain surface)
- **Slipperiness** – how much friction is there
- **Roughness** – how much twisting of the foot or avoidance is required
- **Vegetation** – how much does it impede movement

Sinkage and slipperiness are related to surface type, strength, and weather effects. Roughness however, is due to natural or human induced processes (e.g., erosion, plowing, grading).

Typically surfaces are either man-made pavement (asphalt or concrete) or natural. Most types of natural surfaces are categorized by soil characteristics, although snow and ice must also be considered as another surface category. However, the characteristic used to describe soils relative to mobility are a good starting point for understanding what factors impact movement over varied terrain. A measure of strength is required, as is an index of its slipperiness and roughness. Soil, for mobility purposes, can be describes as fine grain (clays and silts) or coarse grain (sands and gravels) although finer distinctions can be made (e.g. USCS - Unified Soil Classification System, a soil classification system used in engineering and geology).

Load carriage models

Over the past several decades, USARIEM has developed several models for predicting energy costs of locomotion with loads. These models incorporate a range of parameters, including terrain, that determine the energy cost of load carriage. A review of those models is presented below.

The first equation (eq 1) was developed by Givoni and Goldman [1] using the results from numerous human studies:

$$M = \eta(W + L)\left[2.3 + 0.32(V - 2.5)^{1.65} + G\left(0.2 + 0.07(V - 2.5)\right)\right] \qquad \text{[eq 1]}$$

where:

M = metabolic rate, kcal/h
η = terrain factor (= 1.0 for a treadmill)
W = body weight, kg

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L = external load, kg
V = velocity, km/h
G = grade (slope) %

There are several caveats or limits associated with the Givoni and Goldman equation (eq 1). These include a lower limit of 0.7 m/s for V, and an upper limit on the combined external load and walking speed ($L + V$) of 100. In addition there is a calculation for the added costs of loads that are carried on the hands and feet, an adjustment for loads greater than 50 kg, and an equation for the cost of running with load. Those adjustments are beyond the scope of this paper. For the purposes of this paper, the most important aspect of Givoni and Goldman [1] is the introduction of the terrain factor (η).

The tentative values for η defined by Giovoni and Goldman are:

- Hard Surface Road 1.2
- Plowed Field 1.5
- Sand Dunes 1.8
- Hard Snow 1.6

Giovoni and Goldman [1] indicated that more study was needed and that these tentative values might be a function of load (L). As presented later, the first list of η values based on a more adequate database is Soule and Goldman [2].

Pandolf et al. [3] presented an improved or refined equation of metabolic consumption using elements of the Givoni and Goldman equation:

$$M = 1.5W + 2.0(W + L)\left(\frac{L}{W}\right)^2 + \eta(W + L)(1.5V^2 + 0.35VG) \quad \text{[eq 2]}$$

where:

M = metabolic rate (W)
W = subject's weight (kg)
L = load carried (kg)
V = walking speed ($m \cdot s^{-1}$)
G = gradient (%)
η = terrain factor (= 1.0 for a treadmill)

Note: units for M (W) and V (m/s) differ from Givoni and Goldman [1].

In describing the development of this model, Pandolf et al. [3] point out that there are three terms. The first ($1.5W$) is a static term associated with standing, with no load carried, the second term [$2.0(W+L)(L/W)^2$] associated with standing with a load, and the last term (the velocity dependent or dynamic term) is associated with walking and moving the load on the level or uphill with a grade. Note that there was no negative slope data used in its development.

Pimental and Pandolf [4] conducted experiments using a treadmill with several grades (-10 to 25%), loads of 20 and 40 kg, and speeds of 0, 0.5 and 0.9 m/s. They concluded that eq 2 predictions are high for standing conditions, and too sensitive to the influence of loads while standing, and should be revised to predict for negative grades.

Pimental, Shapiro and Pandolf [5] presented data from additional experiments relating to eq 2, suggesting slight revisions, specifically for walking at speeds less than

1.12 m/s (compensating for underestimations) and again for negative slopes. They observed that forcing a subject to maintain a fixed velocity while walking down slopes may actually cause an increase in oxygen consumption as the subject resists gravity. However, no specific changes were made to eq 2.

Santee et al. [6-7], presented a new set of equations for walking on slopes. Using the nomenclature (variables and units) from eq 2, for walking at 1.34 m/s, on level terrain the first equation for level walking is:

$$M_L = 3.28(W + L) + 71.1 \qquad \text{[eq 3]}$$

This equation was modified from Passmore and Durnin [8], which was based on a study that showed no correlation with age, sex, or race. The equation was developed at a walking speed of 1.33 m/s, and Santee et al. [6-7] made the assumption that load can be added directly to the individuals weight. Passmore and Durnin also presented an equation based only on speed, and created a table of speed and weight effects on metabolic rate, using the above equation with a multiplier of V/1.33 m/s, or

$$M_L = [3.28(W + L) + 71.1]\frac{V}{1.33} \qquad \text{[eq 4]}$$

Note there is no separate term for just standing or resting, this is a reflection of Passmore and Durnin [8], who believed that static metabolic rate term should not be separated from the metabolic rate associated with an activity. The Santee et al. [6-7] equation for walking down slopes is:

$$M_D = M_L + 2.4(W + L)gh\left[0.3^{\alpha/7.65}\right] \qquad \text{[eq 5]}$$

where:

g = gravity (9.81 m/s^2)
h = vertical displacement (m/s), or
$= V\sin\left[\operatorname{atan}\left(\frac{G}{100}\right)\right]$
G = grade (%)
α = grade (radians)

Although the velocity is included in the h term, the equation was based on data at only a fixed walking speed of 1.34 m/s, and was not validated for other speeds. Note also that for this down slope case, G and α should be negative.

For walking up slope:

$$M_U = M_L + k(W + L)gh \qquad \text{[eq 6]}$$

where:

k = 3.5 and relates to muscle inefficiency derived from treadmill data.

This equation was developed from the basic work equation, however, Santee et al. [7] when comparing the up slope equation with field data collected on a 8.6% grade, found that the equation under predicted the observed values. The paper also raised the possibility that the terrain coefficient for dirt/gravel roads could have influenced that result.

Santee et al. [9] using the same data as Santee et al. [7], developed a correction factor for eq 2.

$$CF = \eta\left[G(W + L)\frac{V}{3.5} - \frac{(W+L)(G+6)^2}{W} + (25 - V^2)\right] \qquad \text{[eq 7]}$$

This correction factor (CF) is intended to be used when the slope less than or equal to zero in the following form:

$$M = \text{Equation 2} - CF \qquad \text{[eq 8]}$$

The correction factor also used additional data collected during a third study at two speeds (0.89 and 1.12 m/s) and grades of 0, -4, -8.6 and -10.2%) and different load (L) conditions.

TERRAIN FACTORS

This section examines terrain factors and how they are used in USARIEM models for predicting the energy costs of walking and load carriage and specifically the effects of different terrain, using existing data and literature. From this examination, recommendations are provided regarding upgrades or revisions to some terrain factors.

Development of terrain factors:

One of the first efforts to quantify the impact of difference surface condition on the cost of locomotion and load carriage was by Soule and Goldman [2]. They conducted tests on several different level terrains: treadmill, blacktop, dirt road, light brush, heavy brush, swamp and sand. They developed empirical terrain coefficients (η) for the equation developed by Givoni and Goldman [1] (eq 1) to predict the energy of costs of load carriage. Their tests were conducted on a level surface, so G became 0.0 and with some unit conversions presented the following equation:

$$M = \eta(m_t)[2.7 + 3.2(V - 0.7)^{1.65}] \qquad \text{[eq 9]}$$

where:

M = metabolic rate (W)
m_t = total weight: body + clothing + load weight (kg)
V = velocity ($\text{m}\cdot\text{s}^{-1}$)
η = terrain factor (1.0 for a treadmill)

Attempting to reproduce some of Soule and Goldman's analysis resulted in the following:

- Equation 9 may have been simplified for ease of computation. The equation may be expanded to a few more decimal places:

$$M = \eta(m_t)[2.673 + 3.078(V - 0.694)^{1.65}] \qquad \text{[eq 10]}$$

- The terrain factor η was developed from the ratio:

$$\frac{M_{measured}}{M_{predicted\ with\ \eta=1,\ \ Equation\ 9}} \qquad \text{[eq 11]}$$

- Their experiments were conducted with three loads (8, 20, and 30 kg); however, it appears that the values in their tables were based on 0.8 kg instead of 8, and in their first table, 30 kg is presented, but, for the presented values to agree with eq 9, the load must have really been 20 kg. However, it is not clear if these inconsistencies affect the terrain factors, as the measured metabolic rates are not presented (See Table 1 for back calculation of these values).

- They also note that terrain coefficients are relatively independent of speed and load.

- The most important point is that the values of η are empirically based on eq 9.

The non-colored areas of Table 1 present the original data of Soule and Goldman, the red cells are corrected values based upon our calculations, and the yellow cells are also based on our calculation of the averaged measured metabolic rates based on an average *W* of 74 kg. The green cells are the terrain coefficients recommended by Soule and Goldman.

Table 1. Terrain factor data from Soule and Goldman (1972) with back calculation of metabolic rates.

Speed ($m \cdot s^{-1}$)	**0.66**	**0.66**	**0.66**	**1.1**	**1.1**	**1.1**	**1.55**	**1.55**	**1.55**	
Load (kg)	**0.8**	**20**	**30**	**0.8**	**20**	**30**	**0.8**	**20**	**30**	
Predicted	203	257	284	253	320	354	377	483	530	
Eq 1 (Watts)	200	251	278	252	317	350	378	475	526	
Eq 24	202	254	281	255	320	354	385	484	535	
Eq 10*	200	251	278	252	317	350	378	475	526	
Blacktop				0.85	0.93	0.82	1	0.76	0.92	1.0
Dirt road				1.14	1.1	1.18	1.11	0.96	0.98	1.1
Light Brush				1.23	1.37	1.35	1.25	1.19	1.07	1.2
Heavy Brush	1.94	1.58	1.57	1.75	1.62	1.4				1.5
Swamp	2.08	1.99	1.86	2.28	1.68	1.64				1.8
Sand	2.04	2.08	1.84	2.45	2.03	2.11				2.1
Back Calculated Metabolic Rates (W) based on the terrain factors above, Eq. (9), *W* = 74 kg										
Blacktop				214	294	287	378	361	483	
Dirt road				287	348	413	420	456	515	
Light Brush				310	434	473	472	565	562	
Heavy Brush	388	397	436	441	513	490				
Swamp	416	500	517	574	532	574				
Sand	408	523	512	617	643	739				
New terrain coefficients for *L* = 8 kg										
Predicted	221			276			414			
Blacktop				0.78			0.91			
Dirt road				1.04			1.01			
Light Brush				1.12			1.14			
Heavy Brush	1.75			1.60						
Swamp	1.88			2.08						
Sand	1.84			2.24						

Pandolf et al. [3] included a terrain factor (η) in their equation, and showed a plot of their predictions (velocity vs. energy cost). However, they did not show a comparison with their equation and the data from Soule and Goldman. The question is whether the same empirical values hold true? Table 2 compares the Pandolf equation (eq 2) with the data shown in Table 1, which seems to indicate that the terrain factors developed by Soule and Goldman [2] will not apply. It appears that η, when calculated for the Pandolf equation, is inversely dependent on velocity and load. The greatest differences in η are seen when comparing 0.66 velocity to 1.1 m/s data, as related to the V^2 term. This may indicate that the inverse relationships could be attributed to natural (optimal) walking speeds for given loads and terrain compared to tested speeds. Table 2 also presents values of η based on the corrected Pandolf equation, eq 8; the average η values (using the 8-kg load values) are also shown.

Table 2. Comparison of eq 2 with data from Table 1

Velocity (m·s^{-1})		**0.66**	**0.66**	**0.66**	**1.1**	**1.1**	**1.1**	**1.55**	**1.55**	**1.55**
Load		**0.8 (8)**	**20**	**30**	**0.8 (8)**	**20**	**30**	**0.8 (8)**	**20**	**30**
Eq 2 (static)		111 (113)	125	145	111 (113)	125	145	111 (113)	125	145
Eq 2		160 (166)	186	213	247 (262)	295	334	381 (408)	463	520
Surface	η	**Difference (Eq 2 - Back calculated values from Table 1**								
Blacktop	1				33 (27)	1	47	3 (-6)	103	37
Dirt road	1.1				-27 (-38)	-36	-60	-12 (-22)	41	42
Lgt Brush	1.2				-36 (-48)	-104	-101	-38 (-50)	-34	33
Hvy Brush	1.5	-204 (-232)	-180	-189	-126 (-147)	-132	-62			
Swamp	1.8	-202 (-230)	-265	-250	-219 (-249)	-100	-89			
Sand	2.1	-297 (-334)	-269	-224	-221 (-251)	-160	-197			
		Calculated η = (Back Calculated – Eq 2 (static))/(Eq 2 – Eq 2(static))								
Blacktop					0.76 (0.82)	0.99	0.75	0.99 (1.02)	0.70	0.90
Dirt road					1.30 (1.36)	1.31	1.42	1.14 (1.17)	0.98	0.99
Lgt Brush					1.46 (1.52)	1.81	1.74	1.34 (1.37)	1.30	1.11
Hvy Brush		5.67 (5.83)	4.43	4.29	2.43 (2.49)	2.27	1.83			
Swamp		6.24 (6.4)	6.11	5.47	3.41 (3.47)	2.39	2.27			
Sand		6.07 (6.24)	6.48	5.39	3.73 (3.79)	3.04	3.15			
		Calculated η = (Back Calculated – Eq 8 (static))/(Eq 8 – Eq 8 (static))								
Blacktop	0.81				0.69 (0.74)	0.91	0.69	0.94 (0.69)	0.66	0.86
Dirt road	1.12				1.19 (1.22)	1.2	1.31	1.09 (1.11)	0.93	0.94
Lgt Brush	1.37				1.34 (1.37)	1.65	1.60	1.28 (1.29)	1.24	1.06
Hvy Brush	2.93	4.56 (4.53)	3.55	3.50	2.22 (2.25)	2.08	1.68			
Swamp	3.62	5.02 (4.98)	4.89	4.47	3.12 (3.13)	2.18	2.09			
Sand	3.92	4.89 (4.85)	5.18	4.40	3.41 (3.42)	2.77	2.90			

Table 3. Summary of η values obtained for pavement.

Source	Load (kg)	Velocity	η (eq 8)	η ± S.D.	Comments
Table 2	8	1.1	0.74		
Table 2	8	1.55	0.69		
Table 7	8.8	1.34	0.65	0.37	
Table 2	20	1.1	0.91		
Table 2	20	1.55	0.66		
Table 7	22.4	1.34	1.04	0.26	
Table 8	24.9	1.56	1.03	0.11	Average values
Table 2	30	1.1	0.69		
Table 2	30	1.55	0.86		
Table 7	36	1.34	1.02	0.21	
Average			0.83		
Standard Deviation			0.16		

While the terrain factors provide empirical values that represent the influences of terrain on work rates while walking, little information is given regarding how to quantify the terrain. The following sections discuss in more detail specific terrain types.

Pavement

The metabolic rate of walking on pavement has generally been equated to walking on a tread mill, but for some derivations of a terrain factor, (η), the values obtained differed from 1. Pavement has often been tested in conjunction with other surfaces; the values of η for pavement are summarized in Table 3, while the source data is discussed below. In Table 3, the data is sorted by load, and a clear trend between load and η can be seen, with lower loads producing values of η well below 1.0. The average values for these various derivations is 0.83, with the generally accepted value of 1 falling just within one standard deviation of the overall average. However, without additional investigation, a value of 1 for η is the best general option.

Coarse Grain Soil - Sand

It has been recognized for some time that relative to firm surfaces, walking in sand requires additional energy expenditure. Sand also tends to get stronger as its moisture content increases. This effect can be observed when walking on a sandy beach. Close to the water, where waves are impacting the shore, the sand is wet, relatively hard and easier to walk on relative to the dryer beach sand further away from the water.

Lejeune et al. [10] found energy expeditures to be 2.1-2.7 times greater for walking and 1.6 for running on sand relative to a hard surface. These values quantitify how walking and running on sand requires more mechanical energy. They described the sand surfaces as fine (grain size less than

0.0005 m [0.0197 inch], with dry density = 1600 kg/m^3 [100 lbs/ft^3]). Their tests were conducted indoors, and the sand was raked smooth after each subject walked or ran over it. The sand was 0.075-m-deep (3 in.) and had a plastic sheet under it. Since this was indoors, and the layer of sand were uniform with relatively homgeneous materials, it would be expected to be very dry, and thus have low strength. It is not clear if the underlying plastic may have increased the slipperiness of the surface.

Lejeune et al. [10] reported net (above resting) metabolic rates. Based on the plotted values, their average ratio of walking metabolic rate on sand versus firm (concrete indoor track) surfaces was 2.38. They found the optimal walking speed to be 1.1 m/s. By estimating the energy versus velocity data from the plot provided, an equation for the ratio of walking on their firm vs. sand surfaces was determined for the data:

$$\eta = 1.0306 + 2.0341V - 0.6881V^2 \quad \text{[eq 12]}$$

where V is velocity in m/s ($0.85 < V < 2.2$), and yields 2.44 for a velocity of 1.1 m/s. The equation has a peak value η = 2.534 at V = 1.478, with η decreasing as running is approached; this is consistent with their running measurements. Using the data with eq 8 and assuming L = 0, resulted in a regression curve (R^2 = 0.92):

$$\eta = 3.6332V^{-1.704} \quad \text{[eq 13]}$$

Comparing their firm surface data to the dynamic part of eq 8 resulted in a η of about 1 for velocities above 1.6 m/s, with η increasing up to1.9 as velocity decreased to 0.84.

Crowell et al. [11] conducted tests which examined cognitive and physiological performance when carrying loads on pavement, sand and mud. A summary of their soil measurements is in Table 4. The penetrometer used was the standard cone used in vehicle mobility testing [12]. They note that on 1 June, 1.14 cm of rain occurred, probably causing the increase in sand moisture content measured on 3 June. It was stated that some of the fines, smaller and lighter particles, may have been washed out. The mud data will be discussed further in the section on fine grained soils.

The Crowell et al. [11] sand test area was a group of beach volleyball courts which had approximately 6 inches of loose beach sand. As seen in Table 4 the sand had a cone index of 36 near the surface. It was not reported how much the sand was displaced while walking on it (e.g. sinkage or depression). The tests were conducted at a speed of 1.1 m/s, with two different fixed loads, 17.8 kg and 31.97 kg. An increase in metabolic rate was observed as the test progressed over the 1 hour duration. Table 5 shows some of the data converted to Watts, and compared to eq 8, along with values of η calculated from their data. Interestingly, η is seen to be lower for the heavier load, a trend also observed in Table 2.

Table 4. Summary of soil measurements from Crowell et al. (1999).

Date	AM/ PM	Course	Bulk density (lb/ft^3)	Dry density (lb/ft^3)	Percent moisture	Penetrometer (Cone Index, psi)
5/27/1998	AM	Sand	98.6	93.8	5.2	
5/27/1998	PM	Sand	98.2	93.6	5.0	
5/28/1998	AM	Sand	96.4	91.8	5.1	
5/29/1998	PM	Mud	132.3	119.8	10.4	130 @3"
6/1/1998	AM	Mud	124.2	110.0	13.2	
6/1/1998	PM	Mud	128.5	113.3	13.6	
6/3/1998	AM	Sand	99.3	93.1	6.6	36 @1", 144 @3", 300 @6"
6/3/1998	PM	Mud	123.6	110.6	11.7	110 @1", 300 @2"

Table 5. Comparison of data from Cowell et al. (1999) with eq 8.

	Metabolic rate (W)						Equation 8	
	Light_1	Light_A	Heavy_1	Heavy_A		η1	Light	Heavy
Eq 8(static)							138.8	171.1
Eq 8 (Dynamic)							211.9	243.8
Blacktop	368.5	379.7	402.0	424.3		1.0	489.4	585.94
Sand	536.0	547.2	569.5	591.8		2.1	722.5	854.1
Mud	502.5	524.8	569.5	591.8		1.8	658.9	781.0
			η based on eq 8		Avg			
η Blacktop	1.1	1.1	0.9	1.0	1.1			
η sand	1.9	1.9	1.6	1.7	1.8			
η mud	1.7	1.8	1.6	1.7	1.7			

Notes:
[1] These values of η are from Table 1, (recommended by Soule and Goldman [2]).
Yellow cell values based on measured VO_2 converted to Watts using 1 ml O_2 = 20.1 Joules.
Light_1: load = 22.77 kg, VO_2 mean value for 15-30 minutes of the 1 hour test
Light_A: load = 22.77 kg, VO_2 value is the average of the 3 mean values reported during 15-30, 35-40, 55-60 minutes of the test.
Heavy_1 and Heavy_A: same as above, but load was 36.94 kg.

Data from Zamparo et al. [13] show a clear relationship between speed and the ratio of energy cost for walking on beach sand vs. "firm" ground. The moisture content (based on "loss of mass") of the beach sand ranged from 0.64 to 4.88%. No other information is given regarding the test surfaces, except that the test area was a beach. Using their equations for the net energy cost (above resting) of walking at different speeds on sand and firm ground to develop an equation for the ratio, resulted in:

$$\eta = -0.9428 + 3.5481V - 1.0757V^2 \quad \text{[eq 14]}$$

where V is the velocity in m/s ($0.85 < V < 1.95$), and yields 1.66 for a velocity of 1.1 m/s. The equation has a peak value η = 1.98 at V = 1.65, with η decreasing with the transition to running. Equation 14 was created using an assumption that the net energy on firm ground was equivalent to walking on a treadmill (η = 1). Using their sand data to develop a regression equation (R2 = 0.99) for η, based on eq 8, resulted in:

$$\eta = 2.518V^{-0.228} \qquad \text{[eq 15]}$$

Comparing this firm ground data with the dynamic part of eq 8, (i.e. recalculate η) resulted in terrain values close to 1 for velocities greater than ~1.4 m/s, lower values produced higher values of η (up to a value of nearly 1.7, for a velocity of 0.85), which is similar to the firm surface data of Lejeune et al. [10].

Strydom et al. [14] compared metabolic costs for walking on a firm surface (dirt road) and soft desert sand (sand dunes). The data is based on a 3 mile (4.8 km) walk at 1.34 m/s. Other test parameters were an average nude weight of 68.5 kg, and the average load was 23.1 kg. In these experiments, total VO_2 appears to be reported, thus the static part of eq 2 is also taken into account. Table 6 presents the VO_2 intake data and compares it with eq 8. Interestingly, their dirt road data produces a η very close to the values for the heavier loads and higher speeds, in Table 6 The η calculated from their sand data is 2.03, which is clearly lower than the data in Table 2.

Noted previously in regard to eq 1, there was very good agreement for data from sand dunes with η = 1.8, in that equation. The data, based on 4 subjects, was from Daniels and Winnsman [15]. The data, inputted into/with eq 8, yields a value 2.37 ±0.13 (1 SD).

Figure 1 plots the results obtained for various equations and values of η for sand using eq 8. An estimate based on this plot for η is:

$$\eta = 1.5 + \frac{1.3}{V^2} \qquad [16]$$

But, note that this equation does not reflect load and soil strength effects.

Table 6. Comparison of Strydom et al. (1966) data with eq 8 and η.

Surface	O2 intake (l/min)	O2 to Watts (20.1 J/mL O2)	Eq 8 (η = 1)	Eq 2 (static)	Eq 2 (dynamic)	Eq 7 (CF)	η	±SD
dirt road	1.101	368.8	390	122	242	-26	0.92	0.17
sand	1.973	660.9	405	127	253	-25	2.03	0.26

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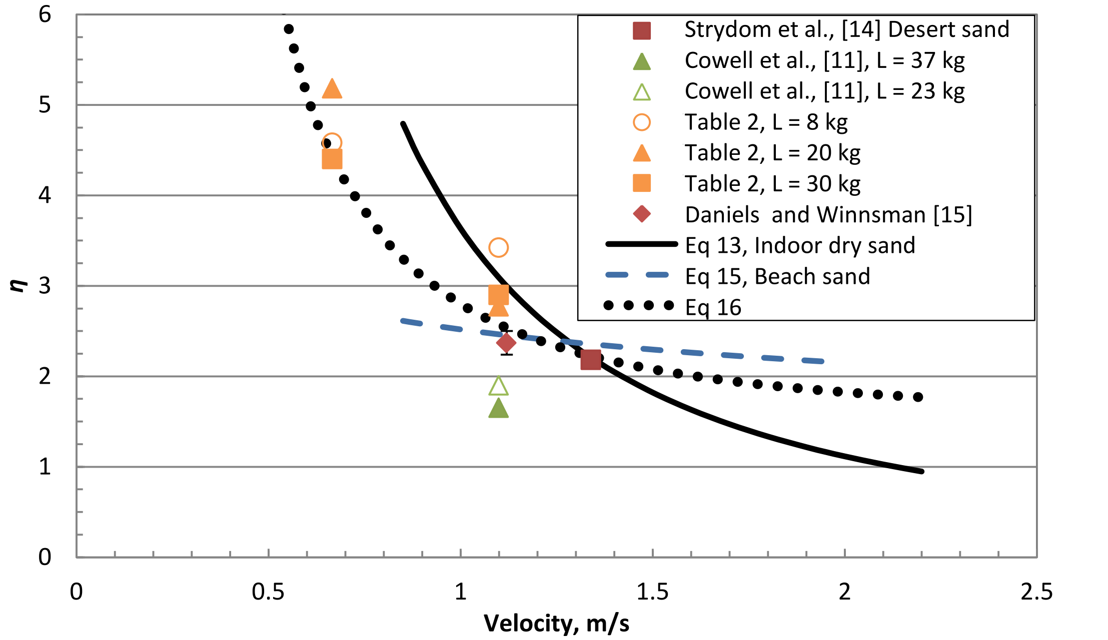
Figure 1. Range of values for η in eq 8, for sand.



Coarse Grain Soil – Gravel and "Dirt Roads"

Well-graded gravel (gravel with a size distribution that minimizes void space) generally makes up the surface of "dirt" roads, unless the dirt road was created only by traffic and without the removal of the native material or addition of gravel. For this discussion "dirt" roads will be those considered consisting only of native material and those that have actually been constructed will be called "Gravel Roads". This distinction has not always been made when reporting terrain conditions during metabolic rate studies, so an attempt will be made by the authors to classify the data into the appropriate category.

Already presented in Table 2, are values of η for a dirt road, based on eq 8. The average value is 1.09, but it ranges from 0.93 to 1.31, with a strong relationship to velocity. Santee et al. [9] when collecting data used in the development of eqs 7 and 8, suggest that η for their rutted dirt road be about 1.2. Interestingly, if using their speeds (0.89 and 1.12 m/s) and loads (0 and 27.2 kg) to pick a value from Table 2, a value of 1.2 would likely be chosen. Santee et al. [7], using the same data as Santee et al. [9], make a case for η being velocity and load dependent. Table 7 presents their data for terrain conditions considered to be gravel or dirt roads (they called it a rough track), note that this data was also used to develop eq 7, but it is not clear if they included a terrain factor during its development. There is lots of scatter in the values calculated for η, and there may be a slight trend associated with load, as noted earlier.

Table 7. η based on the data of Santee et al. (2003a), average weight = 80.2 kg, V = 1.34 m/s.

Terrain Description	Grade (%)	Load (kg)	Filtered Measured cost (W)	Cost ± S.D.	η (eq 8)	η ±S.D.
graded gravel road	-8.6	8.8	302	79	1.14	0.50
graded gravel road	-4	8.8	299	104	0.93	0.55
graded gravel road	4	8.8	561	77	1.08	0.19
graded gravel road	8.6	8.8	934	100	1.36	0.17
graded gravel road	-8.6	22.4	331	52	1.05	0.28
graded gravel road	-4	22.4	351	49	0.96	0.22
graded gravel road	8.6	22.4	1069	113	1.35	0.16
graded gravel road	-8.6	36	313	9	0.68	0.04
graded gravel road	-4	36	343	46	0.69	0.18
graded gravel road	8.6	36	1222		1.35	
Average					1.06	0.25
rough track	-12	8.8	319	69	1.20	0.42
rough track	-12	22.4	369	74	1.20	0.38
rough track	-12	36	328	74	0.73	0.33
Average					1.04	0.38
pavement	0	8.8	288	94	0.65	0.37
pavement	0	22.4	446	78	1.04	0.26
pavement	0	36	516	71	1.02	0.21
Average					0.9	0.28

Daniels et al. [16] compared walking on a treadmill, pavement and a cinder track. They provided individual subjects values, which are reproduced along with calculations of η (based on eq 8) in Tables 8 and 9. The tests were conducted at 1.56 m/s. Higher costs, associated with pavement walking relative to a treadmill, were observed. Based on eq 8, the energy cost of walking on a treadmill is over estimated (values $\eta < 1$), and average value of η for pavement is about 1.

Cinder tracks were used as running surfaces for many years, and some schools still have them. A cinder track may be considered, to be similar to a good gravel road. Daniels et al. [16] reported a 10.3% increase in energy cost between a treadmill and cinder track. Table 9 presents the data, examining the values of η (based on eq 8, with a grade of 0). There is disparity between subjects, but the average η of 1.03 for the treadmill data is consistent with other data, lending support to our intrepretation.

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Table 8. Pavement and treadmill data of Daniels et al. (1953), V = 1.56 m/s

Subject	Weight (kg)	Load (kg)	Paved Road Cost (W)	Treadmill Cost (W)	η (Paved Road)	η (treadmill)
1Ma	63	24.9	475.1	427.4	1.01	0.88
2Ca	80	24.9	521.8	509.6	0.94	0.91
3Mi	67	24.9	490.1	443.1	1.01	0.88
4Hd	62	24.9	496.4	406.2	1.08	0.83
5Hc	75	24.9	530.5	504.0	1.02	0.95
6SM	72	24.9	475.5	469.9	0.91	0.90
7My	51	24.9	431.9	422.2	1.03	1.01
8Br	61	24.9	554.9	476.5	1.26	1.04
Averages	66	24.9	497.0	457.4	1.03	0.92
Standard Deviation					0.11	0.07

Table 9. η calculated from the cinder track data of Daniels et al. (1953)

Subject	Weight (kg)	Load (kg)	Cinder Track cost (W)	Treadmill cost (W)	η (cinder track)	η (treadmill)
1	67	7.68	413.1	347.6	1.07	0.85
2	64	7.68	436.8	438.9	1.21	1.22
3=1 above	63	7.68	401.6	356.3	1.11	0.94
4	62	7.68	446.9	401.3	1.29	1.12
Averages	64	7.68	424.6	386.0	1.17	1.03
Standard Deviation					0.10	0.17

Table 10. Individual subject data from Strydom et al. (1966), walking at 1.34 m/s on level packed dirt road.

Subject	W (kg)	L (kg)	Cost (W)	η
Mah	87.5	20.4	517	1.20
Gro	74.8	27.2	408	0.89
Mat	72.1	23.6	430	1.07
Har	71.7	21.3	414	1.06
Jac	68.5	24.0	324	0.72
Du P	67.6	23.6	308	0.68
De K	64.4	20.9	367	1.00
Smi	63.0	24.0	331	0.81
Roe	50.8	23.6	322	0.93
v. L.	47.2	20.9	267	0.80
Averages	66.8	23.0	369	0.92
Standard Deviation				0.17

The average dirt road data of Strydom et al. [14] was presented earlier. Table 10 shows the individual data from all the subjects walking on the level packed dirt road. The table results indicate considerable variability in the individual calculations of η (based on eq 8). As mentioned earlier the average value of 0.92 (± 0.17 SD), is in agreement of the dirt road, high load and velocity values in Table 2.

Figure 2 combines all the gravel and dirt road calculated values of η, plotted with velocity, from the studies described above. While there may be a minor correlation with velocity, there is not enough range in velocity values to have much confidence in that correlation. The average of all the η values shown is 1.03 ± 0.2 (1 SD), but if only values greater than 1 are averaged, a value of 1.19 ± 0.11 is obtained.

Figure 3 plots the data with load carried, and again no correlation is seen, however, given that the evaluation is limited to only values above 1, a value of about 1.2 would appear to be representative. Additionally, from those two aggregate figures, it does not appear that the data from the various gravel surfaces provide much basis for discrimination between gravel surfaces. The conditions where η values are below 1 might be explained by the surface being dry, smooth, hard-packed providing good traction, effectively approaching a pavement like surface.

Figure 2. Gravel and dirt road values of η compared with velocity

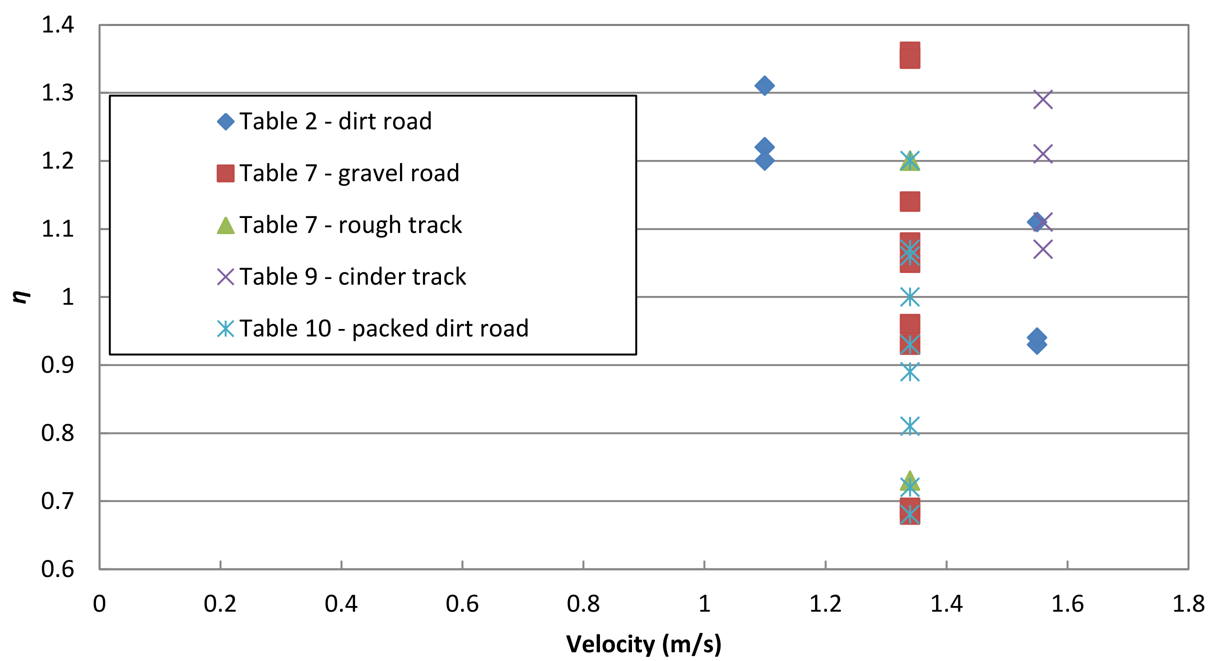

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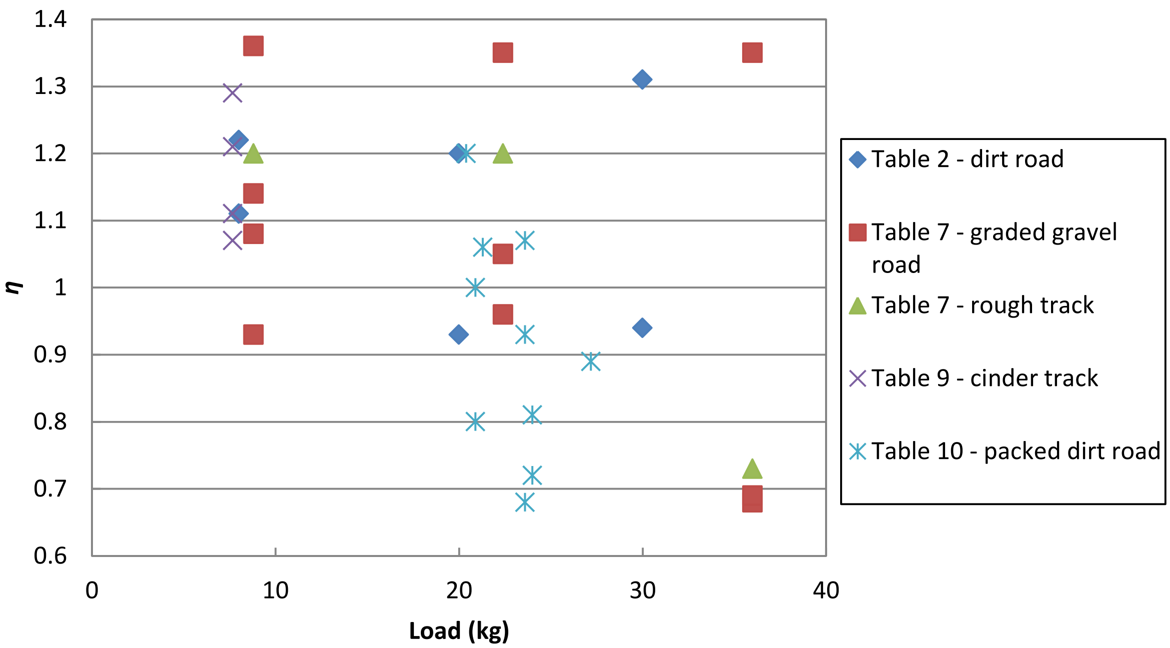
Figure 3. Gravel and dirt road values of η compared with load.



Fine Grain Soil - Clay and Silt

Penetrometer values (Table 4) from Crowell et al. [11] for mud (130 and 110), are unlikely to result in sinkage from human mass, particularly with the 300 value measured at 2 inches (300 is extremely hard soil). The purpose of their mud tests was to examine the influence of slipperiness; reported as an average static friction of 0.45. Static friction values below 0.5 are considered to be noticeablely slippery for humans [17]. Relative to a vehicular perspective, soil which incurs > 0.25 inches of rain in the preceeding 24 hours is considered "slippery", and algorithms that differ from the dry condition algorithms are required. These mud (slippery) values for η (average 1.7) could be attributed to extra effort needed to maintain walking stability either associated with or attributed to a sliding foot.

Rush and Rula [18] examined the relationship of the cone index on how the cone index relates to human walking speed on clay soil. They trained their subjects to learn the effort required to walk at a brisk pace on pavement, then asked them to apply the same muscular effort to walking on clay. The pavement walks alternated with soil test sessions. The average pavement walking pace was 2.08 m/s. The subjects carried no load, except their clothes. The average subject's weight, with clothing, was 75.69 kg. Using input values of L = 0 and V = 2.08 m/s in eq 2 and eq 8 yields a metabolic rate of 605 W. That value is only slightly higher than the voluntary hard work rate of 500 ± 10% reported by Soule and Levy [19]. The walking velocity and cone index of the clay soil were also recorded. The test area was inundated to obtain very low soil strengths, and additional tests where conducted under controlled soil strength and moisture conditions.

Figure 4 presents plots from their data, with a new curve fitted by the authors. Using their velocity values to obtain the dynamic portion of eq 2 (with eq 8), and calculating η results in Figure 5, the equation of the curve is:

$$\eta = 1.0 + \frac{2.5}{(ConeIndex - 4.8)} \text{ for } ConeIndex \geq 7. \quad \text{[eq 17]}$$

The cone index is the average value, for the depth or sinkage of a human footprint, measured from the ground surface to the bottom of the depth of a foot print. For lower cone index values (≤ 7 psi), the terrain should be considered swamp. This equation produces a value of η on the order of 1.02 for a cone index of 110-130 psi., Thus based on the data of Cowell et al. [11], the cone index does not capture slipperiness effects.

Figure 4. Data from Rush and Rula (1967)

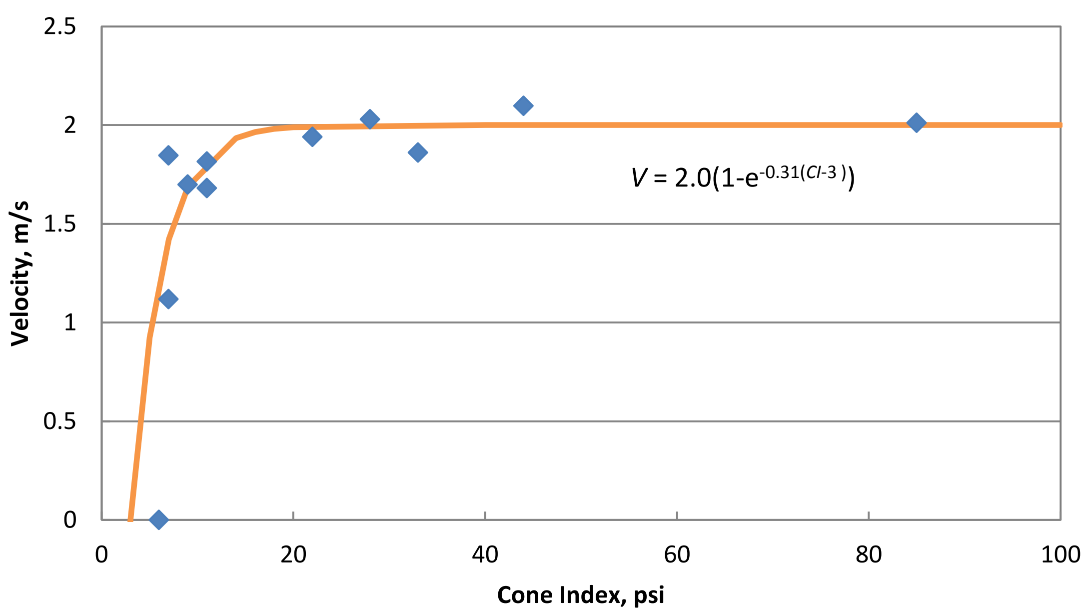
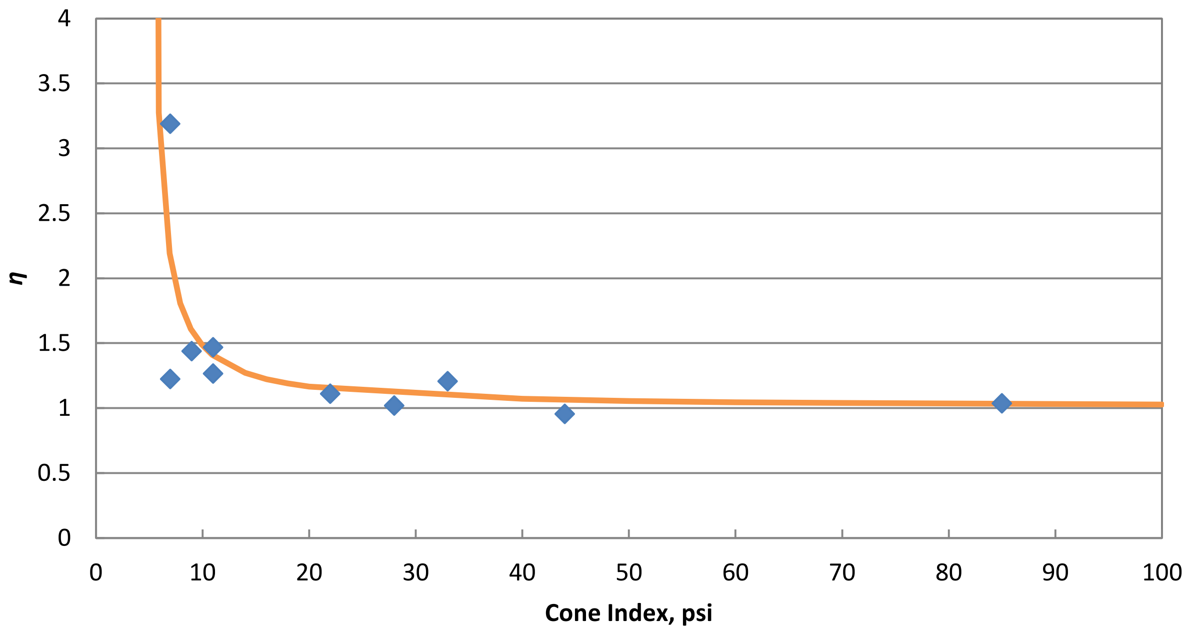


Figure 5. Relationship of η to the cone index of clay soil.



Surface Roughness

It appears that the additional work, as reflected by the terrain factor η, can also be associated terrain roughness. Terrain roughness has been charactertized using several different scales. However, those existing scales are applicable mainly to relatively large digital elevation models. Surface roughness, as used by the NATO Reference Mobility Model (NRMM), is the Root Mean Square (RMS) of terrain elevation, measured at 0.3 m intervals, with slope and long wave length trends removed. Often, the RMS surface roughness is estimated based on terrain feature properties [20], and current work by Durst et al. [21-22], discusses the measurement and estimation of roughness for vehicle ride quality, based on Light Detection and Ranging (LIDAR) data. From a vehicle perspective, surface roughness causes vehicle vibration, which can cause driver discomfort, and may result in slower speeds. The question for human movement is the determination of an appropriate roughness scale and index, and to quantify the effect of roughness on metabolic costs.

Voloshina et al. [23] conducted treadmill experiments which had blocks of wood attached to simulate rough terrain. They reported 30% increase energy requirement compared to a smooth treadmill. While it would be interesting to calculate a value for η, they have yet to formally report enough detail to accomplish that [24]. This appears to be the only study available, which does not have other effects (e.g. cinder track and dirt roads, clearly have a roughness component, but the roughness is inherent). If the roughness of such magnitude as to require a higher step, (e.g., step over a fallen log), and then end up at the nearly the same elevation, there does not appear to any applicable published literature.

Vegetation

Walking though vegetation can increase metabolic rate by several mechanisms: 1) stems and branches may be pushed out of the way or broken, 2) snags or hobbling of feet and clothing, 3) more pliant vegetation may not just resist forward movement , but actually push or spring back, 4) low branches or fallen debris may need to be stepped over, 5) thorns, branches or stronger brush or trees may force route deviation, redirection or detours, and 6) the roughness of the debris may cause additional effort as discussed above. Table 2, contains terrain coefficient values for heavy and light vegetation using the corrected Pandolf equation (eq 8), based on the data of Soule and Goldman [2].

One of the tests of Rush and Rula [18] was conducted on sparse low growing vegetation, with high enough soil strength, so that the soft soil effect might be ignored. For that test, η was estimated to be 1.13. Paysant et al. [25] presented data for pavement, mown grass, and tall grass for subjects walking (self-paced). They saw little difference between walking on pavement and a smooth lawn, but there was a significant difference when walking on "untended, uneven (grass height 12-20 cm maximum). Although separate values for weight and load were not given, it can be assumed that the only load was clothing and instrumentation. Values for η were estimated as: pavement – 0.82, mown lawn – 0.9, and untended grass – 1.4.

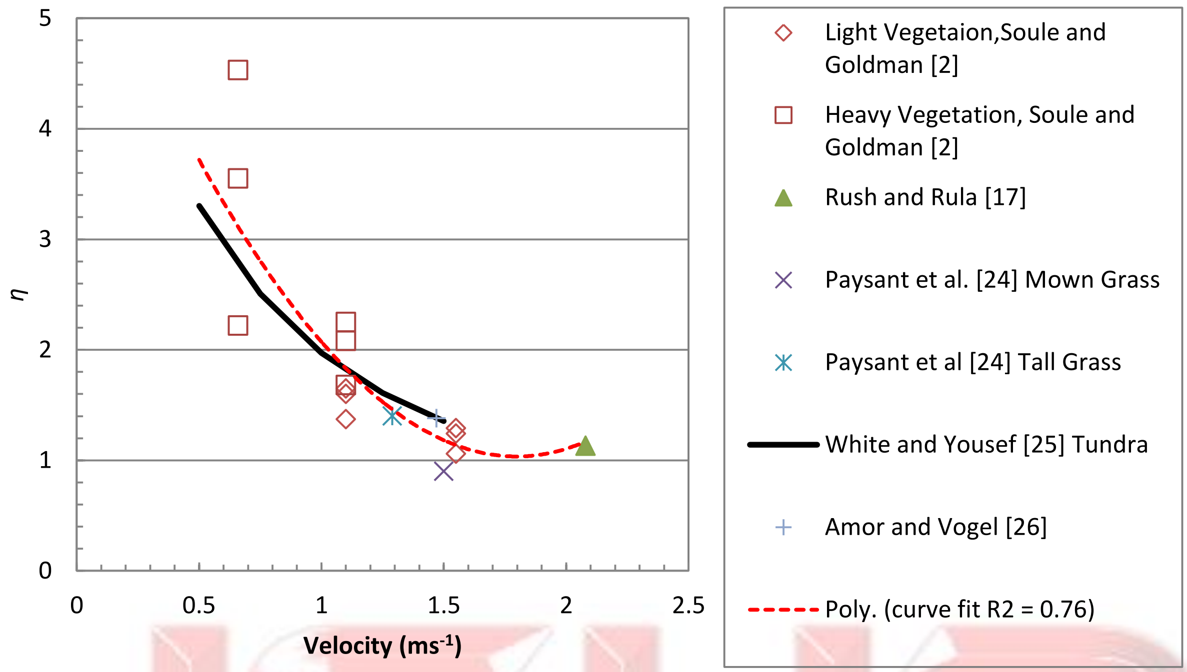
White and Yousef [26] while investigating the metabolic rate of reindeer, obtained some human data for walking on dry tundra and on well a packed road, as described above. The dry tundra had a thin dry moss layer, small tussocks (1-5 cm tall and 5-10 cm diameter) and ground litter of twigs and grasses. They fit curves to their VO_2 data as a function of velocity. Assuming L and G = 0, η was computed using eq 8.

Amor and Vogel [27] presented a complete set of data obtained to compare ways of carrying a shoulder-fired missile, with data obtained on a treadmill and on "level ground with rough grass" with traversals in both directions, and at their subjects "best possible speed". Using eq 8, with grade = 0, the η-value was 1.1 for L = 3.71 kg, 1.1 for L = 40.81 kg on a treadmill and 1.38 for L = 40.81 in rough grass.

The aggregate of all η-values for vegetation as a function of velocity and data source are shown in Figure 6. Given that the results for all the vegetation except heavy vegetation is similar in nature, the strong relation to velocity suggests that all of the data can be combined into one equation:

$$\eta = 0.0718V^3 + 1.3V^2 - 5.3701V + 6.0705 \quad \text{[eq 18]}$$

Figure 6. Comparison of η values for vegetation.



DISCUSSION

A general observation particularly applicable to this study is the importance of a multi-disciplinary approach to problems. This paper used existing data but applied insight from other disciplines to enhance, or gain additional insight. The basis for this paper is anchored in the biological disciplines, human and other animal physiology, biomechanics, and ecology, but also incorporated geology and soil sciences, meteorology, physics and engineering. In this paper, the combined background and experience of the sources used constitute a fairly comprehensive and multi-disciplinary approach.

The authors used published data as well as derived values, and fitted trend lines to data, or otherwise interpreted studies which may differ relative to the original data. The latter is a key aspect of this paper, which is both a strength and weakness, in that it is based on existing data in previously published research papers. This paper demonstrates the importance of cross-disciplinary communication and collaboration by bringing knowledge of surface characteristics and vehicle mobility to bear on the energetics and biomechanics of human locomotion. The present trend [28] is to provide access to the supporting data for published studies. In addition, in the US, there is a directive to eventually provide public access to the data from all government sponsored research. One concern regarding this accessibility is that secondary parties that use the data may not be aware of the nuances of the original research and data collection.

This is a potential intellectual "slippery slope" of an entirely different nature. In part this issue reflects the nature of many scientific publications which are written in a very concise manner and are directed towards an informed, and often very specific readership. Ideally, each study would have a supporting report describing the test design, methods, actual testing, including confounding issues, and additional summary or even de-identified individual data which may not have been relevant to the main publications.

Equation 2 with the correction factor (eq 7) for grades less than or equal to zero as the accepted metabolic rate equations within the USARIEM's SCENARIO-J simulation is currently used for prediction of metabolic rate. For walking on various terrain surfaces, η, based on the above comparisons and analyses, should be calculated based on the recommended equations or values presented in Table 11. In these equations, the velocity (V) should be in m/s.

However, note that there is very little data to support the use of these values on slopes other than zero. For some terrain types, there may also be an additional influence of load and velocity that is not taken into consideration.

It is possible that the effect of terrain, other than slope, should be an additive value (as a function of velocity) and not a multiplier to the dynamic part of eqs 2 and 7. But, evaluating that hypothesis is beyond the scope of this work, and is only suggested as a future approach.

Table 11 represents a necessary step towards incorporating better science into models used to estimate the effects of terrain on the energetics of human locomotion. Terrain factors for walking surfaces has been a neglected area of research which was not using the available science from other disciplines to improve energy cost estimates for walking and load carriage.

As per earlier points in this discussion, an important aspect of this paper is the use of existing data to revise or develop new terrain factors and provide an initial basis for validating models with the modified or improved terrain factors. It is often valuable to design and execute new studies, but given the resources in time and funding, using existing data is a reasonable and economical first step. As researchers consider the collection of additional data to validate or expand the classes of terrain factors, hopefully this review and expansion of terrain factors provide a clear indication of the effort and resources required to conduct an adequate series of outdoor studies of load carriage on sand, snow, mud, marshes, gravel, rock and scree, and moderate to heavy brush over varying topography.

In terms of future development, incorporation of these new terrain factor developments into other existing energy cost models such as those of that address steeper slopes [29] complex terrain [30], and stream crossings [31] is recommended. Other factors that may be incorporated into models include the impact of weather on surface conditions and the individual or population being modeled, load related factors such as load distribution or proportional loading, and the target population, and clothing effects such as impediment of motion (hobbling), or footwear design. Broader areas of interest include the impact of varying terrain on energy costs and the biomechanics of movement may set limits on the speed of movement, maximum and optimum loads, and the potential for injuries relative to walking speed, load and terrain.

Just as the terrain factor is a component of the energetics of locomotion and activity, energy costs are a component of whole body physiological models. Improved terrain factors can be used not only in more comprehensive, but complex physiological models, but in simple computer applications on smart phones, route planning tools, simulations and other serious gaming for the users such as anthropologists, aid works, hikers and backpackers, and for military planning and operations.

Table 11. Recommended Values for η for use in eq 8.

Terrain Description	η	Comments
Rough Terrain	unknown	Assume surface roughness affect is embedded in the η selected for the terrain.
Slippery Terrain	1.7	Hard wet clay, ice
Vegetation	$\eta = 0.0718V^3 + 1.3V^2 - 5.3701V + 6.0705$	
Swamp	3.5	Based on Table 2 and Figure 5 for very low cone index
Paved Roads	1.0	See Table 3, there is variability and possibly a relationship to load and velocity
Gravel Roads	1.2	
“Dirt” Roads	1.2	
Sand	$\eta = 1.5 + \frac{1.3}{V^2}$	See Figure 1, for range of values, weaker sand will have higher values.
Silts and Clays	$\eta = 1.0 + \frac{2.5}{(ConeIndex - 4.8)}$ for $ConeIndex \geq 7$	For Cone Index ≤ 7 assume it is a swamp

DISCLAIMER

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