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Terrain coefficients for predicting energy costs of walking over snow

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ABSTRACT

Background: Predicting the energy costs of human travel over snow can be of significant value to the military and other agencies planning work efforts when snow is present. The ability to quantify, and predict, those costs can help planners determine if snow will be a factor in the execution of dismounted tasks and operations. To adjust predictive models for the effect of terrain, and more specifically for surface conditions, on energy costs, terrain coefficients (η) have been developed. The physiological demands of foot travel over snow have been studied previously, and there are well established methods of predicting metabolic costs of locomotion. By applying knowledge gained from prior studies of the effects of terrain and snow, and by leveraging those existing dismounted locomotion models, this paper seeks to outline the steps in developing an improved terrain coefficient (η) for snow to be used in predictive modeling.

Methods: Using published data, methods, and a well-informed understanding of the physical elements of terrain, e.g., characterization of snow sinkage (z), this study made adjustments to η-values specific to snow.

Results: This review of published metabolic cost methods suggest that an improved η-value could be developed for use with the Pandolf equation, where $z = \text{depth}$ $(h)*(1$ - (snow density $(\rho_0)/1.186))$ and $\eta = 0.0005z^3 + 0.0001z^2 + 0.1072z + 1.2604$.

Conclusion: While the complexity of variables related to characteristics of snow, speed of movement, and individuals confound efforts to develop a simple, predictive model, this paper provides data-driven improvements to models that are used to predict the energy costs of dismounted movements over snow.

1. Introduction

Activities in snowy environments generally require more energy than similar activities in more moderate or warm conditions. Day et al. (2012) indicated that the increased demand could be up to 20%, further stating: “increase in total caloric requirements is mainly caused by increased physical exertion, because it is unlikely that cold exposure itself, in an adequately clothed individual, increases energy requirements more than 10%”. Baker-Fulco (1995) suggested that due to the increased energy requirements, military personnel may be unable to maintain adequate caloric intake in the cold.

Physiological studies of dismounted movement in snow typically characterize snow conditions descriptively. This may be due to the fact that snow is difficult to quantify. Even at present, measurement of snow properties, such as snow fall and depth, use relatively simple instruments and methods. A dated (60 + yr) Snow, Ice and Permafrost Research Establishment (SIPRE) Instruction manual (SIPRE, 1954) describes a snow kit for measuring snow properties. With only a slight change to the spring scales, the same kit and the same observations are still in use today. The key properties of snow include depth (h), sinkage (z), slipperiness, and strength or density (ρ); which is closely related to moisture content and grain characteristics.

The terrain coefficient (η) was developed to adjust human energy cost predictions for different surface conditions. The concept of η for dismounted movements and load carriage was introduced by Givoni and Goldman (1971) and defined more clearly by Soule and Goldman (1972). Richmond et al. (2015) reviewed and refined η for common surface conditions (e.g., pavement, gravel, packed dirt, sand, and mud). By exploiting existing knowledge of snow properties and surface physics derived from vehicle locomotion studies can be used to develop improved η-values for snowy terrain.

The essential research on η for physiological modeling was conducted 1972–1979 at the US Army Research Institute of Environmental Research (USARIEM) and translated into usable models. This paper

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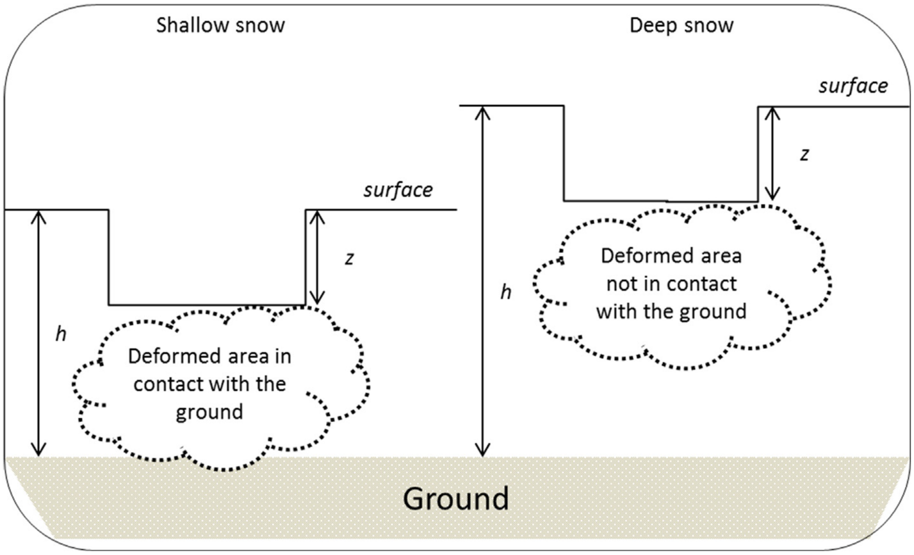

Fig. 1. Deep and shallow snow, determined by interaction of deformed snow with the ground.

briefly reviews the existing USARIEM equations for prediction of energy cost of walking, the origin of η, and then refines η-values specific to snow using knowledge of snow and surface physics from vehicle locomotion studies, and existing data from multiple human studies of snow walking.

2. Materials and methods

2.1. Load carriage models

From 1971 to 2003, several load carriage models were developed at USARIEM. These models incorporate multiple parameters, including terrain, to determine the energy cost of load carriage. A brief overview of the most relevant models is presented and a more detailed description of these models and how are used to evaluate and refining terrain coefficients is presented in Richmond et al. (2015).

Equation (1) was developed by Givoni and Goldman (1971):

$$M = \eta\,(W + L)\,[2.3 + 0.32\,(V - 2.5)^{1.65} + G\,(0.2 + 0.07\,(V - 2.5))] \tag{1}$$

where M is the metabolic rate (kcal·h^{-1}), W is body mass (kg), L is the external load (kg), V is the velocity or speed of walking (km·h^{-1}) and η is a non-dimensional terrain coefficient. For the purposes of this paper, the most important aspect of Givoni and Goldman (1971) is the introduction of the terrain coefficient (η). The concept of η is based on a relative scale, using a non-dimensional (ND) η value of 1.0 for walking on a treadmill; while a proposed initial η value of 1.6 was suggested for hard snow.

The first improved list of η values is Soule and Goldman (1972). The η-values developed by Soule and Goldman (1972) were for level terrain in the context of Givoni and Goldman (1971). As described in Richmond et al. (2015), a modified version of Eq. (1) was developed for level ground, the basis for all of the Soule and Goldman (1972) η-values, by setting G = 0%, adjusting for different units for V (m·s^{-1}) and M (W):

$$M = \eta(W + L)\,[2.673 + 3.078\,(V - 0.694)^{1.65}] \tag{2}$$

Using elements from Givoni and Goldman (1971), Pandolf et al. (1977) presented a refined equation of metabolic cost:

$$M = 1.5W + 2.0(W + L)\left(\frac{L}{W}\right)^2 + \eta(W + L)(1.5V^2 + 0.35VG) \tag{3}$$

where variables are the same as those from Givoni and Goldman (Eq. (1)) except for different units in M (W), V (m·s^{-1}), and the addition of grade (G) for the uphill slope or gradient (%).

The equation from Pandolf et al. (1977) is currently the more widely recognized model for predicting energy costs of load carriage. Later models from Pimental and Pandolf (1979), addressed a primary limitation of the Pandolf et al. equation (Eq. (3)), indicating it did not address negative (downhill) grades. To address the downhill grade limitation of the Pandolf et al. (1976) equation, Santee et al. (2003) developed a correction factor (CF) for Eq. (3):

$$CF = \eta\,[G\,(W + L)\,V / 3.5 - ((W + L)\,(G + 6)^2)\,/\,W + (25 - V^2)] \tag{4}$$

This CF is intended for use when the slope is ≤ 0 in the following form:

$$M = \text{Eq.3} - CF \tag{5}$$

2.2. Terrain coefficient for snow

2.2.1. Walking in shoes or boots

In addition to load carried and grade, there are other parameters that can influence the work rate and walking velocity. In snow, these parameters include snow depth (h), density (ρ), slipperiness (traction), and type and weight of footwear and winter clothing.

Snow depth and the amount a person sinks into the snow are important relative to the effort required to walk in it. In Fig. 1, shallow snow is presented as a combination of snow density and the depth where the layer of snow that is deformed or compacted by stepping on it reached the ground, essentially producing firm resistance against further sinkage and provides a firmer surface to push of/against to move forward. In deep snow, the deformed layer is not in contact with the ground, and more or less floats above un-deformed snow, so there is more potential to sink further overtime, or more pressure associated with a heavier load.

Skis and snowshoes were developed specifically to make movement over snow covered surfaces easier by reducing sinkage, as even moderate reductions in sinkage can reduce energy costs. However, predicting sinkage is difficult, as it is dependent on both snow h and ρ. Haehnel and Shoop (2004) outlined snow response to load and issues associated with describing snow ρ. Describing snow ρ is not a well-defined process, though there are several indices which can be used.

If it is assumed when walking in snow the front half of the foot supports the entire walker's mass during each step, and represents the