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Original research

The Pandolf equation under-predicts the metabolic rate of contemporary military load carriage

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ABSTRACT

Objectives: This investigation assessed the accuracy of error of the Pandolf load carriage energy expenditure equation when simulating contemporary military conditions (load distribution, external load and walking speed).
Design: Within-participant design.
Methods: Sixteen male participants completed 10 trials comprised of five walking speeds (2.5, 3.5, 4.5, 5.5 and 6.5 $\text{km}\cdot\text{h}^{-1}$) and two external loads (22.7 and 38.4 kg).
Results: The Pandolf equation demonstrated poor predictive precision, with a mean bias of 124.9 W and −48.7 to 298.5 W 95% limits of agreement. Furthermore, the Pandolf equation systematically under-predicted metabolic rate ($p < 0.05$) across the 10 speed-load combinations. Predicted metabolic rate error ranged from 12–33% across all conditions with the 'moderate' walking speeds (i.e. 4.5–5.5 $\text{km}\cdot\text{h}^{-1}$) yielding less prediction error (12–17%) when compared to the slower and faster walking speeds (21–33%).
Conclusions: Factors such as mechanical efficiency and load distribution contribute to the impaired predictive accuracy. The authors suggest the Pandolf equation should be applied to military load carriage with caution.

1. Introduction

There is a universal requirement for military personnel to move their body weight plus an external load both continuously over a prolonged duration and intermittently at high speed.[1,2] Recent evidence suggests that military load carriage requirements are increasing, with advancing technologies and personal protective equipment contributing in part to this burden.[3] The high metabolic demands of occupational tasks involving load carriage are well-documented.[4–6] It is not necessarily possible however, to directly translate these previous results to current and/or future load carriage tasks because they do not capture all the factors that impact upon energy cost and an individuals' capacity for load carriage.[7,8] That said, it is also not practical that well-controlled research trials are undertaken prior to each military activity, hence the value of robust predictive tools. To estimate the energy cost of load carriage tasks, practitioners can use metabolic equivalent tables,[9] heart rate derived energy expenditures[10] and predictive models.[11,12] These tools vary in both their ease of use and their accuracy. The ability to predict the energy cost of military load carriage with some precision would greatly assist timely mission planning and personnel management.

Pandolf et al.[11,13] established a model from experimental data collected from a series of studies to predict the energy cost of loaded (up to 70 kg) walking on level and graded terrain (up to 25%) up to a speed of 9.0 $\text{km}\cdot\text{h}^{-1}$. A series of coefficients were also established to accommodate different terrain surfaces (i.e. asphalt, dirt road, light brush, heavy brush, swampy bog and loose sand) when employing this predictive equation.[14] This model considers several task inputs, including; individual body mass, total load carried, walking speed, terrain surface and terrain gradient in estimating energy cost. Further work has resulted in the development of a correction factor for downhill gradients.[15] The accuracy of this equation has subsequently been assessed by several studies. The trial conditions (external load, gradient terrain, walking speed and load distribution) across these studies has varied, however three[16–18] (out of the four) have reported poor agreement between predicted and measured metabolic rate during load carriage. Furthermore, these three studies observed that predicted metabolic rate was under-estimated ($p < 0.05$), when compared to measured metabolic rate. These results however, do not appear to demonstrate a pattern

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for the magnitude of under-prediction of metabolic rate. In the field, under-prediction of metabolic rate could lead to an underestimation of task demands,[8] potentially compromising the physical wellbeing of personnel and/or jeopardising mission success due to physical fatigue.

The Pandolf equation was based upon backpack load carriage only, however contemporary military load carriage typically involves load distributed over the torso (e.g. backpack, body armour, webbing), hands (e.g. weapon, tools), head (e.g. helmet, night vision goggles) and feet (e.g. boots).[3] The distribution of external load is known to influence the energy cost for a given load carriage task.[19–21] Loads distributed close to an individual's centre of mass are metabolically more efficient, when compared to equivalent peripheral loads.[19–22] Load position on the back has even been shown to affect energy cost of load carriage, with loads higher on the back eliciting a lower energy cost during level walking when compared with loads positioned around the lower back.[23,24] The predictive validity of the Pandolf equation may therefore be diminished when applied to the current military context. Two studies have assessed the accuracy of the Pandolf equation under load conditions relevant to contemporary military load carriage (e.g. backpack, webbing, body armour, rifle), however walking speeds were fixed.[18,25] Interestingly, the results from these studies were mixed, with one study finding good agreement between predicted and measured metabolic rate during load carriage[25] and another showing poor agreement.[18] The explanation for this apparent disparity is not immediately clear.

To date, the accuracy of the Pandolf load carriage equation has not been systematically evaluated under contemporary military load carriage conditions across various walking speeds. The ability to confidently apply this model to military scenarios would prove invaluable in mission planning, e.g. duration of operations, work to rest schedules, total load limits and nutritional requirements as well as the physical preparation of personnel. The aims of the current study were therefore, to; (1) assess the magnitude and direction of error of the 'Pandolf' load carriage equation across 10 load × walking speed combinations, (2) assess the agreement between measured and predicted metabolic rate, and (3) describe the relationship between walking speed and metabolic rate. Based on current evidence it was hypothesised that the 'Pandolf' load carriage equation would under-estimate metabolic rate during simulated military load carriage. The second hypotheses was that increasing walking speed would elicit an exponential as opposed to a linear increase in metabolic rate during load carriage.

2. Methods

Sixteen healthy male subjects (data are mean ± SD, $n = 16$, Age; 32.6 ± 5.8 years; body mass; 85.9 ± 8.2 kg; height 1.82 ± 0.06 m; peak aerobic power ($\dot{V}O_{2peak}$) 51.3 ± 5.0 mL·kg^{-1}·min^{-1}) completed the study. Two additional male participants were recruited but they failed to complete all trial conditions (6.5 km·h^{-1}) and were removed from all analysis. Sample size calculations indicated that 12 participants would have an 80% power to detect a difference between methods of 24 W ($p < 0.05$). All participants were informed of the purpose and potential risks associated with participation prior to providing written informed consent. All procedures were conducted in accordance with Australian Defence Human Research Ethics Committee requirements.

All participants performed an incremental exercise test on a motorised treadmill (Austredex Treadmills, AC 888 Marathon Runner, Australia) to determine peak oxygen uptake ($\dot{V}O_{2peak}$). The exercise protocol was based on a previously described method.[20] Briefly, following a warm-up the peak aerobic power test commenced at a comfortable running speed as self-selected by the participant. The speed was increased by 1 km·h^{-1} every 60 s until (self-determined) maximum steady state running speed was reached, beyond this point speed was held constant and gradient was increased by 1° every 60 s until volitional exhaustion. Expired air samples were collected continuously throughout the test for determining oxygen uptake (ParvoMedics Inc. TrueOne 2400, U.S.). All peak respiratory variables were obtained by averaging the values recorded in the last 30 s of exercise. Heart rate was measured continuously via telemetry with a transmitter and receiver (Polar-Electro, Finland). Before each test, the gas analysers were calibrated using gases of known composition. The ventilometer was calibrated for volume using a 3-L Hans-Rudolph volumetric syringe over 5 flow rates ranging from 50 L·min^{-1}–500 L·min^{-1}. All baseline testing was conducted within 14 days of the experimental trial.

Participants arrived at the laboratory at 8 am on the morning of testing. Subjects were weighed (Biospace, Inbody 230, USA) in their underwear and had body composition assessed via bioelectrical impedance. A heart rate chest transmitter (Polar-Electro, Finland) was fitted. Subjects completed 10 walking bouts of 15 min under different speed and load conditions: five walking speeds (2.5, 3.5, 4.5, 5.5, 6.5 km·h^{-1}) and two external loads (22.7, 38.4 kg). The walking speed range reflects several relevant military tasks including patrolling (2.5–3.5 km·h^{-1}), approach marches (4.5–5.5 km·h^{-1}) and movement whilst engaged (6.5 km·h^{-1}). The external loads were developed in consultation with the Australian Army and based upon representative load lists for patrol and marching order (22.7 and 38.4 kg respectively).

The participants completed the marching assessments in disruptive pattern combat uniform and combat boots. The 22.7 kg external load was distributed between webbing (chest or hip), torso body armour and weapon (replica F88-SA1). The 38.4 kg external load was distributed between webbing (chest or hip), backpack and weapon. Subjects completed all 22.7 kg trials before the 38.4 kg conditions, with a 15 min rest period between walking speeds across both load conditions. The two sets of load conditions were separated by at least 45 min rest to allow metabolic rate to return towards resting levels. The presentation of walking speed within each load condition was randomised across all participants. Expired air samples were collected continuously for each condition for determining oxygen uptake ($\dot{V}O_2$) via open-circuit spirometry (ParvoMedics Inc. TrueOne 2400, U.S.). Heart rate was measured continuously via telemetry with a transmitter and receiver (Polar-Electro, Finland) and reported as 15-second averages. Laboratory conditions were maintained at 21 ± 1 °C and 39 ± 4% relative humidity. An oscillating fan was used to minimise thermal stress and subjects were free to consume water *ad libitum* between trials. Participants body mass was measured prior to both the 22.7 and 38.4 kg trials to ensure equivalent hydration status across trials.

The Pandolf load carriage equation[11] was used to predict the metabolic rate of load carriage via the following equation;

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

where M = metabolic rate, watts; W = subject weight, kg; L = load carried, kg; V = walking speed, m/s; G = grade, %; η = terrain factor (terrain factor: 1.0).

The measured metabolic rate (MR) was calculated from steady state oxygen uptake (min 10–15) using the following equation;

$$\textit{Metabolic rate (watts)} = (\dot{V}O_2 \times 5.0)/0.0143$$

Percentage prediction error was calculated between measured and predicted metabolic rate, where MR_M = metabolic rate measured and MR_P = metabolic rate predicted;

$$\text{Prediction error (\%)} = ((MR_M - MR_P)/MR_M) \times 100$$

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