TITLE
Accuracy of Metabolic Cost Predictive Equations during Military Load Carriage

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ABSTRACT

To quantify the accuracy of five equations to predict the metabolic cost of load carriage under ecologically valid military speed and load combinations. Thirty-nine male serving infantry soldiers completed thirteen, 20-minute bouts of overground load carriage comprising of two speeds (2.5 and 4.8 $km\cdot h^{-1}$) and six carried equipment load combinations (25, 30, 40, 50, 60, and 70 kg), with 22 also completing a bout at 5.5 $km\cdot h^{-1}$ carrying 40 kg. For each speed-load combination the metabolic cost was measured using the Douglas bag technique, and compared to the metabolic cost predicted from five equations; Givoni & Goldman, 1971 (GG), Pandolf et al. 1997 (PAN), Santee et al. 2001 (SAN), American College of Sports Medicine 2013 (ACSM), and the Minimum-Mechanics Model (MMM), Ludlow & Weyand, 2017. Comparisons between measured and predicted metabolic cost were made using repeated measures ANOVA and Limits of Agreement. All predictive equations, except for PAN, under-predicted the metabolic cost for all speed-load combinations (p<0.001). The PAN equation accurately predicted metabolic cost for 40 and 50 kg at 4.8 $km\cdot h^{-1}$ (p>0.05), under-predicted metabolic cost for all 2.5 $km\cdot h^{-1}$ speed-load combinations as well as 25 and 30 kg at 4.8 $km\cdot h^{-1}$, and over-predicted metabolic cost for 60 and 70 kg at 4.8 $km\cdot h^{-1}$ (p<0.001). Most equations (GG, SAN, ACSM, MMM) under-predicted metabolic cost while one (PAN) accurately predicted at moderate loads and speeds, but over-predicted or under-predicted at other speed-load combinations, indicating that caution should be applied when utilising these predictive equations to model military load carriage tasks.

Keywords: speed-load combinations, dismounted-infantry, exercise, performance

INTRODUCTION

Load carriage, defined as walking, running, or a combination of both with a torso mounted load (8), is a principal combat related task of military personnel that can be critical to mission success (16). Despite the ongoing development of military technology to reduce combatant load, the total load mass (equipment load [webbing, body armour, rucksack] and base layer mass [clothing and boots]) carried by modern soldiers have continued to increase (16, 21). The ability to predict accurately the metabolic cost of load carriage is important for organisations to task manage effectively (26), optimise nutrient intake (17), and minimise performance losses through excessive workloads (18).

Bobbert (7) developed an equation to predict the metabolic cost of unloaded human locomotion at different movement speeds (2.1-6.9 $km \cdot h^{-1}$), and gradients (0-12%). Subsequent equations have included occupational relevant elements, such as terrain coefficients, equipment mass, and load distribution. To date, the 'Pandolf Equation'(23) (PAN), is the most widely used to predict the metabolic cost of load carriage (3, 20). The PAN was developed from an equation first proposed by Givoni and Goldman (15) (GG), which accounted for terrain, gradient, and equipment load. The GG equation also adjusted for metabolic cost from increased equipment load, mass distribution (away from the torso) and higher speed-load combinations. The PAN equation has since been modified and validated several times to account for running speeds up to 11.5 $km \cdot h^{-1}$ (14), and for a wider range of terrain gradients (22, 30).

The metabolic cost of load carriage estimated from the PAN equation has been compared with measured data across a range of military relevant speed-load combinations, in laboratory and field settings, involving military personnel (18, 25, 27), healthy adults (19, 20, 34), and in personnel wearing a self-contained bomb disposal ensemble (3). Recently, the PAN equation has been reported to under-predict the metabolic cost by 12-17% at moderate walking speeds (4.5 km·h^{-1}), and by 21-33% at slower and faster speeds (2.5 and 6.1 km·h^{-1} respectively), when Australian soldiers carried tactical loads of 22.7 and 38.4 kg (12). These findings were consistent with other investigations demonstrating similar magnitudes of under-prediction in the metabolic cost of load carriage (3, 18, 20, 25), thus questioning the accuracy of the PAN equation.

Alternative equations have been developed and compared with PAN for their accuracy in predicting metabolic cost. Ludlow and Weyand (19) compared the predictive accuracy of the PAN, American College of Sports Medicine's equation (1) (ACSM), and their own Height-Weight-Speed (HWS) equation, using grouped means from 127 previously published research studies. They found the ASCM and PAN equations under-predicted metabolic cost in almost all instances, with the standard error of the estimate almost four times greater than the HWS equation. While the HWS equation was initially developed for unloaded walking only, Ludlow and Weyand (20) further developed this model to account for both equipment load and walking gradient, and subsequently referred to their model as the Minimum-Mechanics Model (MMM). When the MMM was compared to ACSM and PAN, it was found to predict more accurately metabolic cost in healthy individuals. Another comparative study by Potter et al. (26) compared the predictive abilities of the GG, PAN, Santee et al. (29) (SAN), and ACSM equations at two different work intensities (350 and 540 w). Similar differences in root mean square error and mean absolute error were reported across all four equations.

The studies above (12, 19, 26) have compared the accuracy of some predictive equations across limited speeds and loads; in efforts to improve predictability with new equations (20, 27). However, comparisons between the GG, PAN, SAN, ACSM, and MMM predictive equations, using military personnel, in a field based environment, and across a broad range of military relevant load-speed combinations have not been investigated previously. The aim of the present study was to compare the measured metabolic cost of load carriage across an ecologically valid range of military-specific speed-load combinations (10), in serving military personnel, with the metabolic cost estimated from five widely employed load carriage equations: GG, PAN, SAN, ACSM, MMM. It was hypothesised that all predictive equations would under-predict the metabolic cost of load carriage when compared to measured data; principally due to the limited load and speed ranges associated with the development of each equation.

METHODS

Experimental Approach to the Problem

Subjects were assigned to cohorts based on their Ground Close Combat role (RM, PARA, Lt Inf, RAF Regt), and data were collected in each cohort on separate occasions. On day one, subject's stature and body mass were measured wearing issued physical training kit (t-shirt and shorts). The subjects then completed a Multi-Stage Fitness Test which involved repeatedly running 20 m shuttles at an increasing speed until volitional exhaustion (28). Subjects $\dot{V}O_{2max}$ was estimated from the number of shuttles they completed on this test (28). At least 24 h after the Multi-Stage Fitness Test subjects performed a minimum of 10 and a maximum of 13, 20-minute bouts of overground load carriage, with equipment load conditions ranging from 25-70 kg, at speeds of 2.5, 4.8, and 5.5 $km \cdot h^{-1}$ (Table 1). Speed-load combinations were completed in a sequential mass order, with each mass completed at each of the load carriage speeds prior to progressing to the subsequent load mass. Load carriage bouts were completed over one to three days; depending on environmental conditions and subject availability. The lighter speed-load combinations (25-40 kg at 2.5, 4.8 and 5.5 $km \cdot h^{-1}$) were typically completed on the first day, with the remaining speed-load combinations (50-70 kg at 2.5 and 4.8 $km \cdot h^{-1}$) completed on the second day. All subjects wore a standardized base layer comprising of an undershirt, combat trousers, combat jacket, and boots (4.1 kg). For each equipment load iteration (Table 1), the load was distributed between fixed waist worn webbing, a weapon (SA80) partially supported by a sling, and body armour (totalling 25 kg). This equipment load represents 'Assault Order', which is the minimum load carried by dismounted infantry during load carriage (5). To achieve other heavier equipment load iterations (>25 kg), additional mass was carried in a rucksack.

Subjects

A total of 42 serving male infantry soldiers volunteered to participate and 39 were included in the final analysis, due to exclusion of three subjects for incomplete datasets. The 39 subjects (mean ± SD, age = 27 ± 5 yr, stature = 1.79 ± 0.05 m, body mass [corrected nude] = 83.5 ± 8.0 kg, estimated maximal aerobic capacity [$\dot{V}O_{2max}$] = 51.8 ± 5.0 $mL \cdot kg^{-1} \cdot min^{-1}$) were serving personnel from the United Kingdom's (UK) Armed Forces Ground Close Combat roles (Royal Marines [RM], Parachute Regiment [PARA], Light Infantry [Lt Inf], and Royal Air Force Regiment [RAF Regt]). The study was approved by the Ministry of Defence Research Ethics Committee (*Application No: 804MoDREC17*) and was conducted in accordance with the declaration of Helsinki (36). Subjects were informed of the risks and benefits of the study prior to any data collection and then signed an institutionally approved (Ministry of Defence Research Ethics Committee) informed consent document.

Load Carriage Bouts

Subjects completed 10 to 13, 20-minute bouts of overground load carriage, with equipment load conditions of 25, 30, 40, 50, 60, and 70 kg at 2.5 and 4.8 $km \cdot h^{-1}$, as outlined in Table 1. A non-completion of a bout was recorded if subjects self-withdrew or were withdrawn by the researchers due to either not being able to maintain the required pace or were perceived to be unsafe carrying the load. The RM and PARA cohorts (n = 22 combined) completed an additional role-specific 20-minute stage at 5.5 $km.h^{-1}$ with an equipment load of 40 kg. The speeds were representative of a patrol (2.5 $km \cdot h^{-1}$), forced march (4.8 $km.h^{-1}$), and insertion march (5.5 $km.h^{-1}$) as observed in infantry soldiers (33). All bouts were completed on a level grass surface and paced by a Physical Training Instructor using a handheld Global Positioning System (Garmin eTrex 10, Garmin [Europe] Ltd, UK), with each bout separated by a minimum of 10 minutes' rest. Subjects consumed water *ad libitum* between load carriage bouts.

*** Insert Table 1 near here ***

Expired gas was collected using the Douglas bag technique, using single 200 L Douglas bags (Cranlea Human Performance Limited, UK) attached to the subjects back (clipped to backpack or webbing). Collection occurred during the final four minutes for bouts at 2.5 $km \cdot h^{-1}$ and two minutes for bouts at 4.8 and 5.5 $km \cdot h^{-1}$. Prior to use, Douglas bags were flushed with ambient air, and fully evacuated. Respiratory gas fractions were analysed (Servomex 5200, Servomex, UK), and then volume (Harvard dry gas meter, Harvard Apparatus, USA) and temperature recorded (digital thermometer; Fisher Scientific, UK). The gas analyser was calibrated using a two-point calibration, following the manufacturer's instructions.

Equations

The measured $\dot{V}O_2$ data were converted to watts, using the equation described in table 2, and compared to the metabolic cost estimated from each of the predictive equations (Table 2). Nude body mass was estimated by subtracting issued physical training kit mass (t-shirt and shorts, 0.45 kg) from measured body mass on day one. For all metabolic cost equations, total load (to the nearest 0.1 kg) was used. Total load was the equipment load plus the mass of a standardised base layer (4.1 kg). The resulting mean total load for each equipment load condition was 29.6 ± 1.9, 34.6 ± 1.9, 45.0 ± 2.3, 56.1 ± 2.8, 66.1 ± 2.8 and 76.1 ± 2.8 kg (Table 3). For clarity these loads are referred to as their target equipment load conditions (i.e. 25, 30, 40, 50, 60, and 70 kg) throughout unless stated otherwise. For secondary analysis, equipment load conditions were grouped as, 'light' (25 and 30 kg), 'medium' (40 and 50 kg) and 'heavy' (60 and 70 kg). A terrain factor of 1.3 (16) and 1.2 (24) (grass surface) was applied for the GG and PAN, respectively. Whilst the ACSM equation does not account for total load, the estimated metabolic cost was corrected for in the same manner as the MMM (Table 2).

*** Insert Table 2 near here ***

Statistical analysis

Data were analysed using International Business Machine's Statistical Package for the Social Sciences (v23, IBM, UK). Subjects with greater than 25% of metabolic cost data missing were excluded from the analysis (n=3). To manage missing data of included subjects (8%), multiple imputation procedures were conducted using a modified version of the procedures described by van Ginkel and Kroonenberg (32). Missing values at random were imputed using linear regression, with the mean of all five imputations used for the analysis. All data were checked for normality and examined for homoscedasticity by visual inspection of scatterplots. Repeated measures Analysis of Variance (ANOVA), with Greenhouse-Geisser correction, was used to test for significant three-way and two-way effects and interactions (of speed x load x measurement method [measured and estimated], speed x measurement method, and load x measurement method) for measured and estimated metabolic cost using the five predictive equations (Table 2). Where significant interactions were found, paired samples t-test were conducted with a Bonferroni adjustment to identify differences between measured and estimated metabolic cost. Agreement between the measured and estimated metabolic cost of load carriage across the different speed-load combinations was assessed using Bland and Altman (2) mean bias and 95% Limits of Agreement (LoA), presented as forest plots, and differences assessed with unadjusted paired samples t-tests. Where the equipment loads were later grouped as 'light' (25 and 30 kg), 'medium' (40 and 50 kg), and 'heavy'(60 and 70 kg), a correction was applied to the LoA due to repeated observations for speed and equipment load comparisons (6). The predictive error (Table 2) of each equation compared to measured values were calculated to determine the level of precision between measured and estimated metabolic cost. Data are presented as mean ± 95% confidence intervals (95% CI) unless stated otherwise and statistical significance was set at $p<0.05$.

RESULTS

Environmental conditions for the trials were (mean ± SD [range]): ambient temperature, 15.9 ± 2.4 ºC (12.1-19.1 ºC); relative humidity, 76.4 ± 15.5% (53–100%); air speed, 1.6 ± 0.9 $m \cdot s^{-1}$ (0.2-2.8 $m \cdot s^{-1}$).

Interaction effects were found for speed x load x measurement method ($F_{3.394,128.980}$ = 11.965, $p<0.001$), speed x measurement method ($F_{1.121, 42.587}$ = 692.693, $p<0.001$), and load x measurement method ($F_{2.704, 102.756}$ = 76.731, $p<0.001$), with a main effect for measurement ($F_{1.309, 49.726}$ = 282.292, $p<0.001$). Table 3 shows a significant mean bias between measured and predicted metabolic cost for all predictive equations. The GG, SAN, ACSM, and MMM equations consistently under-predicted metabolic cost at all loads and speeds by varying amounts.

*** Insert Table 3 near here ***

Table 3 shows the measured metabolic cost at the different speed-load combinations. Differences between speeds (2.5 $km \cdot h^{-1}$ vs. 4.8 $km \cdot h^{-1}$) at the same load were found for all loads ($p<0.001$), with a higher metabolic cost measured with an increase in speed.

The PAN equation showed a mean bias between measured vs. predicted metabolic cost for all loads at 2.5 km·h^{-1} and 5.5 km·h^{-1} as well as 25, 30, 60 and 70 kg at 4.8 km·h^{-1} (p<0.001). The PAN equation under-predicted metabolic cost for all loads at 2.5 km·h^{-1} and 5.5 km·h^{-1} and 25 and 30 kg at 4.8 km·h^{-1}, but over-predicted metabolic cost for 60 and 70 kg loads at 4.8 km·h^{-1} (Table 3). On the other hand, the PAN equation accurately predicted metabolic cost for 40 and 50 kg loads at 4.8 km·h^{-1}. The PAN equation demonstrated the lowest percentage of predictive error for 60 and 70 kg loads at 2.5 km·h^{-1} (~12-14%), 25-50 kg loads at 4.8 km·h^{-1} (~1-11%), and 40 kg at 5.5 km·h^{-1} (~8%).

Figure 1 shows mean bias and 95% LoA for the measured vs. predicted metabolic cost for all five equations when the loads were grouped (light = 20 and 30 kg; medium = 40 and 50 kg; heavy = 60 and 70 kg) and compared across two speeds, 2.5 km·h^{-1} and 4.8 km·h^{-1}. The PAN equation accurately predicted the mean metabolic cost for medium loads at 4.8 km·h^{-1} (p=0.18), under-predicted the mean metabolic cost for all loads at 2.5 km·h^{-1} and the light loads at 4.8 km·h^{-1}, but over-predicted the mean metabolic cost for the heavy loads at 4.8 km·h^{-1} (p<0.001). The ACSM, GG, SAN, and MMM equations consistently under-predicted metabolic cost for all loads and speed combinations (p<0.001) when grouped in this manner.

*** Insert Figure 1 near here ***

DISCUSSION

This study measured the metabolic cost of load carriage in soldiers over an ecologically valid range of reported combat speed-load combinations (10) and compared these data with those predicted by a number of commonly used predictive equations. As stated earlier, the accurate prediction of the energy cost of load carriage is important for operational success since it provides data to improve task management, assure proper caloric/nutrient intake, and minimize performance losses. The GG, SAN, ACSM, and MMM equations consistently under-predicted metabolic cost at walking speeds of 2.5 km·h^{-1}, 4.8 km·h^{-1}, and 5.5 km·h^{-1}, carrying equipment loads between 25-70 kg. In contrast, the PAN equation accurately predicted metabolic cost for 40, and 50 kg loads at 4.8 km·h^{-1}. The PAN equation, however, under-predicted metabolic cost for all loads at 2.5 km·h^{-1}, 25 and 30 kg at 4.8 km·h^{-1} and 5.5 km·h^{-1}, while over-predicting the metabolic cost for, 60, and 70 kg loads at 4.8 km·h^{-1}. The MMM equation appears to most accurately predict the metabolic cost for 25-50 kg loads at 2.5 km·h^{-1}, whereas the PAN equation most accurately predicts metabolic cost for 60 and 70 kg loads at 2.5 km·h^{-1}, 25-70 kg loads at 4.8 km·h^{-1}, and 40 kg at 5.5 km·h^{-1}. The inconsistencies in the direction of error when predicting metabolic cost using the PAN equation may limit its application for modelling the metabolic cost of load carriage in military personnel.

Previous studies have focused on comparing a measured metabolic cost of load carriage with a single predictive equation (3, 12, 25), best effort velocities (18), and/or equipment loads relative to body mass (18, 20). The findings of the present study are similar to those reported by Drain et al. (12) who demonstrated that the PAN equation under-predicted metabolic cost for walking speed-load combinations ranging from 2.5 – 6.5 km·h^{-1} and loads at 22.7 and 38.4 kg. The present study also found the PAN equation under-predicted metabolic cost for load carriage activity for all loads at 2.5 km·h^{-1} and some loads at 4.8 km·h^{-1}, and 5.5 km·h^{-1}. We also showed that the PAN equation over-predicted metabolic cost for heavier equipment loads

(60 and 70 kg), but accurately predicted the metabolic cost for medium equipment loads (40 and 50 kg) at 4.8 $km \cdot h^{-1}$. Explanations for the discrepancies between study findings might be due to differences in population (e.g. military vs. non-military) and testing conditions (field vs. laboratory). For example, the paper by Drain et al. (12) utilised a military population in a laboratory setting, whilst the study by Ludlow and Weyand (20) utilised healthy adult subjects in a laboratory setting. Nevertheless, the present study found the PAN equation to have the least predictive error at speeds of 4.8 $km \cdot h^{-1}$, and 5.5 $km \cdot h^{-1}$ when compared to the metabolic cost predicted from the other equations at the same speeds. In addition, we showed the PAN equation better predicted metabolic cost at speeds of 4.8 $km \cdot h^{-1}$, and 5.5 $km \cdot h^{-1}$ when compared to 2.5 $km \cdot h^{-1}$, as reported by others (12).

The GG, SAN, ACSM, and MMM equations consistently under-predicted metabolic cost during load carriage activity for all speed-load combinations by varying amounts (Table 3). Despite under-predicting metabolic cost, however, the MMM equation demonstrated the lowest predictive error for light (25, 30 kg) to medium (40-50 kg) equipment loads at 2.5 $km \cdot h^{-1}$. Conversely, the SAN equation demonstrated the highest predictive error for the majority of the speed-load combinations. One explanation for the intra-equation differences in predicted metabolic cost might be a result of both the development and elements contained within each of the assessed equations. The MMM model for example includes both a component for resting metabolic rate, minimum walking metabolic cost and a speed dependent element, which is an approach not taken in the other equations investigated within this study. A similar three element approach has been employed during the update to the Load Carriage Decision Aid for the American Army (17). Importantly, the MMM does not include a component for load *per se* and instead corrects with a multiple of body mass based on the ratio between body mass and body mass plus total load (Table 2), an approach we also employed when using the ACSM equation. This approach therefore provides equal weighting to all aspects of mass and does not differentiate between body mass and equipment load. Conversely, the PAN, GG, and SAN all separate total/equipment load from body mass within their equations.

Equipment load and its inclusion within the five equations is likely to contribute significantly to both the intra-equation and measured-predicted differences in metabolic cost (12). It is well known that the distribution of equipment load plays a significant role in its resulting metabolic cost, particularly those away from the centre of mass (e.g. feet, hands, and the head (9, 31, 35)). In the present study, load mass was distributed across the hands (SA80 rifle [~4.5 kg]), body (fatigues, webbing [9.5 kg], body armour [~9 kg]), the back (rucksack [dependent on the carried load mass iteration]), and the feet (military boots, ~1.8 kg). This distribution is very common for modern soldiers, however it differs significantly from the rucksack only loads used when developing the GG, PAN, SAN, and MMM equations. With the exception of the correction factors for the GG equation, the corresponding alterations in metabolic cost of this load distribution were accounted for. In addition, in the present study the base layer mass was included in the subsequent analysis, this was not the case for all of the equations during their development, which again may explain some of the metabolic cost variance between investigations and between measured and predicted values. Finally, as highlighted by Potter et al. (26), the corresponding rise in metabolic cost of load is not solely due to the load itself but also a result of the increased thermal burden (11), an effect not considered by any of the equations. It is important to acknowledge that depending on the subjects (trained vs non-trained, military vs civilian) undertaking the task, its duration, and the prevailing environmental conditions there may be an increase in metabolic cost, due to thermal burden, which would contribute to an even greater error in predictive results.

The results of the present study demonstrate that no single equation appears to be best suited for accurately predicting the metabolic cost of load carriage across a range of ecologically valid speed-load combinations. A limitation of the current study is the possible carryover effect on metabolic rates from preceding load carriage bouts. However, the authors believe this would have been minimal given that all subjects were highly-trained specialist infantry soldiers who regularly carried similar loads over longer periods. We were able to ensure the rest periods between bout within each day were similar to those authors who have reported them (e.g. Drain et al. (12)), thereby allowing meaningful comparisons. Further investigations should identify whether an equation hybrid approach is more suitable or whether the development of a new equation is required. This is an important step, to inform their use, particularly with emerging technologies being designed to support and inform commanders in the field. For example, Potter et al. (14) have already demonstrated the utility of these predictive equations in combination with Global Positioning System data to predict the metabolic cost of movement over the complex terrains, typically experienced in military operations.

The primary aim of this study was to assess the metabolic cost of load carriage at different speed-load combinations on a level surface. Consequently, future investigations should compare equations under differing gradients. Equally, in the present study, data of unloaded walking was not collected. We were therefore unable to assess the most recent predictive equation, a meta-regression, from Looney et al. (17). Furthermore, it should be acknowledged that the assessment of the predictive equations herein does not account for the influence of cardiovascular drift, due to the short bouts of load carriage administered within this investigation. The influence of cardiovascular drift has been demonstrated to result in an increased metabolic cost for prolonged exercise at an intensity greater than 50 % $\dot{V}O_{2max}$ (4, 13, 24). Thus, it could be proposed that with an increased load carriage duration the equations assessed would subsequently further under predict metabolic cost, when speed-load combinations result in a metabolic rate greater than ~50 % $\dot{V}O_{2max}$.

Conclusion

Our findings showed that most equations (GG, SAN, ACSM, MMM) under-predicted metabolic cost while one (PAN) accurately predicted at moderate loads and speeds, but over-predicted or under predicted at other speed-load combinations. This has important implications for effective task management (26), informing nutrient intake requirements (17), and overall mission success. While the PAN equation accurately predicted metabolic cost for a typical paced march speed-load combination (40 and 50 kg at 4.8 $km \cdot h^{-1}$), it under- and over-predicted metabolic cost for all other speed-load combinations including that of typical patrolling (40 kg at 2.5 $km \cdot h^{-1}$) thereby demonstrating inconsistencies in its predictive ability. These results indicate that the inaccuracies and/or inconsistencies of the predictive equations limit their application to model military load carriage. Future research should investigate how combinations of predictive equations or correction factors could be applied to most accurately estimate the metabolic cost of load carriage for specific military populations and their associated load carriage ensembles. This in turn would enable the integration of data collected from wearable technologies (such as global positioning systems) into predictive equations and algorithms, in order to obtain accurate metabolic data at the individual level.

PRACTICAL APPLICATIONS

Equations from the peer reviewed literature can be used to predict the metabolic cost of load carriage. However, the accuracy of these equations has previously been questioned, especially when used outside of the population from which they have been developed. This study shows that the commonly used Pandolf Equation most accurately predicts the metabolic cost of load carriage at 40 and 50 kg at 4.8 $km \cdot h^{-1}$ but over- and under-predicts outside of this range. Caution should therefore be applied when utilising these predictive equations.

Specifically, the intended use of the predicted metabolic cost data should dictate whether the magnitude of predictive error is acceptable for the given task.

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Table Captions

Table 1 – An overview of the speed-load combinations for each ground close combat role.

Table 1 – An overview of the speed-load combinations for each ground close combat role.

Load Carriage Speed ($km{\cdot}h^{-1}$)	2.5						4.8						5.5
Equipment Load Mass (kg)	25	30	40	50	60	70	25	30	40	50	60	70	40
Royal Marines	X	X	X	X	X	X	X	X	X	X	X	X	X
Royal Air Force Regiment	X	X	X	X	X	X	X	X	X	X	X	X	
Parachute Regiment	X	X	X	X	X	X	X	X	X	X	X	X	X
Light Infantry	X	X	X	X	X	X	X	X	X	X	X	X	

Notes: n = 39 for 2.5 $km{\cdot}h^{-1}$ and 4.8 $km{\cdot}h^{-1}$; n = 22 for 5.5 $km{\cdot}h^{-1}$. Crosses indicate completed and non-completed speed-load combinations respectively.

Table 2 - An overview of the predictive and supplementary equations utilised within this research.

Reference	Model Acronym	Predictive Equation
Givoni & Goldman, 1971 (15)	GG	$MC = \mu\ (M_S + M_L) \times [2.3 + 0.32(V - 2.5)^{1.65} + G(0.2 + 0.07(V-2.5))]$ $+ MC = K \times M_L^2 \times V^2$ - *Correction for weapon mass in hands (K = 0.015)* $+ MC = 0.4\ (V \times M_L - 100)$ - *Correction for M_L–speed product > 100*
Pandolf et al, 1997 (22)	PAN	$MC = 1.5M_s + 2\cdot(M_s + M_L) \times (M_L/M_s)^2 + \mu(M_L + M_S) \times (1.5V^2 + (0.35VG))$
Santee et al, 2001 (29)	SAN	$MC = (0.0661V+0.115) \times 3.28(M_S + M_L) + 71.1$
ACSM, 2013 (1)	ASCM	$MC = (0.1V + 1.8VG) + 3.5$ *$MC \times (M_S + M_L) / M_S$ – to take into account the M_L (as used in the MMM)*
Ludlow & Weyand, 2017 (20)	MMM	$MC = MR_{Rest} + (C1 \times G) + MR_{WalkMin} + (1 + (C2 \times G)) \times (C3 \times V^2)$ *$C1 = 0.32$ $C2 = 0.19$ $C3 = 2.66$ $MR_{WalkMin} = 3.28$* *$MC \times (M_S + M_L) / M_S$ – to take into account the M_L*
Reference		Supplementary Equation
Potter et al. (27)		$MC\ (W) = MC\ (\dot{V}O_2) \times 5 / 0.0143$
ACSM (1)		$MC\ (W) = MC\ (kcal\cdot h^{-1}) \times 0.86$
Drain et al. (12)		Predictive Error = ((MC[measured] – MC[estimated] / MC[measured]) x 100

Abbreviations: MC, Metabolic Cost (W for PAN and SAN; $mL\cdot kg^{-1}\cdot min^{-1}$ for MMM and ACSM; and $kcal\cdot h^{-1}$ for GG); M_S, participant nude body mass (kg); M_L, total load (kg); V, walking speed ($m\cdot min^{-1}$ for ACSM; $km\cdot h^{-1}$ for GG; $m\cdot s^{-1}$ for PAN, SAN and MMM); G, walking gradient (%); μ, terrain factor; K, constant for location of M_L mass; MR_{Rest}, metabolic rate at rest; $MR_{WalkMin}$, minimum walking metabolic rate; C, constant. For the SAN equation there are additional elements to the equation for estimating the MC of uphill and downhill walking. These are not presented as only level walking was investigated in the current study.

Table 3 - Mean bias ± 95% confidence intervals and predictive error for each predictive equation at each speed-load combination.

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Speed ($km \cdot h^{-1}$)	Target Carried Load (kg)	Actual Mean Total Load (kg)	Measured Metabolic Cost (W)	GG		PAN		SAN		ACSM		MMM	
				Mean Bias ± 95% CI (W)	Predictive Error (%)	Mean Bias ± 95% CI (W)	Predictive Error (%)	Mean Bias ± 95% CI (W)	Predictive Error (%)	Mean Bias ± 95% CI (W)	Predictive Error (%)	Mean Bias ± 95% CI (W)	Predictive Error (%)
2.5	25	29.6 ± 1.9	367 ± 53	-72 ± 89*	19.7	-113 ± 91*	30.8	-82 ± 91*	22.4	-62 ± 88*	17.0	-53 ± 91*	14.5
	30	34.6 ± 1.9	406 ± 44	-98 ± 77*	24.1	-135 ± 78*	33.2	-111 ± 77*	27.4	-88 ± 77*	21.6	-78 ± 78*	19.2
	40	45.0 ± 2.3	447 ± 52	-107 ± 87*	24.0	-131 ± 92*	29.3	-132 ± 90*	29.7	-101 ± 88*	22.5	-90 ± 87*	20.1
	50	56.1 ± 2.8	460 ± 75	-83 ± 146*	18.0	-81 ± 161*	17.6	-125 ± 144*	27.2	-84 ± 145*	18.4	-73 ± 142*	15.8
	60	66.1 ± 2.8	527 ± 60	-116 ± 120*	21.9	-76 ± 138*	14.4	-174 ± 118*	32.9	-125 ± 120*	23.7	-113 ± 116*	21.3
	70	76.1 ± 2.8	613 ± 94	-167 ± 189*	27.2	-72 ± 207*	11.8	-240 ± 187*	39.2	-183 ± 189*	29.9	-170 ± 185*	27.8
4.8	25	29.6 ± 1.9	560 ± 61	-82 ± 93*	14.6	-41 ± 93*	7.4	-118 ± 94*	21.0	-103 ± 92*	18.4	-109 ± 94*	19.5
	30	34.6 ± 1.9	571 ± 74	-64 ± 129*	11.2	-23 ± 129*	4.0	-112 ± 130*	19.6	-93 ± 129*	16.4	-100 ± 130*	17.5
	40	45.0 ± 2.3	612 ± 78	-47 ± 142*	7.6	5 ± 142	-0.8	-119 ± 143*	19.4	-93 ± 143*	15.2	-100 ± 144*	16.3
	50	56.1 ± 2.8	687 ± 79	-59 ± 154*	8.6	19 ± 164	-2.8	-158 ± 151*	22.9	-123 ± 152*	17.9	-131 ± 149*	19.0
	60	66.1 ± 2.8	726 ± 81	-42 ± 160*	5.8	75 ± 178*	-10.4	-165 ± 157*	22.7	-123 ± 158*	16.9	-131 ± 155*	18.0
	70	76.1 ± 2.8	821 ± 122	-81 ± 248*	9.9	92 ± 256*	-11.2	-227 ± 245*	27.6	-178 ± 247*	21.6	-186 ± 244*	22.6
5.5#	40	45.8 ± 1.9	807 ± 98	-130 ± 174*	16.1	-63 ± 172*	7.9	-262 ± 178	32.5	-238 ± 177*	29.5	-229 ± 176	28.4

Notes: Where GG, Givoni and Goldman (15) equation; PAN, Pandolf et al. (22) equation; SAN, Santee et al. (29) equation; ACSM, ACSM (1) equation; MMM, Ludlow and Weyand (20) equation;. Total load is presented as Mean ± SD. *Mean Bias is presented as mean bias ± 95% CI.* [#] *n = 22 due to only the Royal Marines and Air Assault roles completing this load-speed combination. * Significant mean bias between actual and predicted MC, $p<0.05$*

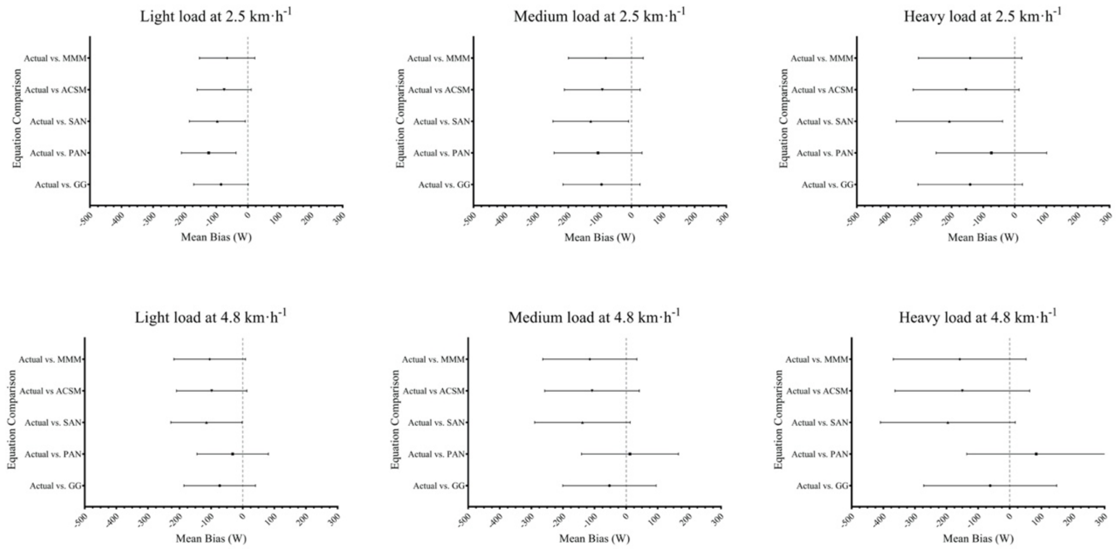

Figure 1 - Forest plot of the mean bias and 95% confidence intervals for measured vs. predicted metabolic cost for all five predictive equations across the 3 equipment load groupings and two speeds.

Where: GG, Givoni and Goldman (15) equation; PAN, Pandolf et al. (23) equation; SAN, Santee et al. (29) equation; ACSM, ACSM (1) equation; MMM, Ludlow and Weyand (20) equation. Equipment loads were grouped as: light=25 kg and 30 kg; medium= 40 kg, and 50 kg; heavy=60 kg and 70 kg.