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ASSESSMENT OF THE RELATIONSHIP BETWEEN RUCKSACK LOAD AND STANDING METABOLIC RATE

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14. ABSTRACT

There is a lack of quantitative data describing the impact that added load has on an individual's standing metabolic rate. Fourteen male US Army Soldiers (age 21 ± 2 years; height 174 ± 7 cm; body mass 73 ± 10 kg) stood 6 minutes with four loads (0, 22, 44, and 66% body mass) while wearing a respirator mask connected to a metabolic cart. Oxygen uptake was not significantly different between the 0% and 22% BM loads ($p = 0.294$) but was significantly higher with the 44% BM load versus both 0% BM and 22% BM ($p < 0.05$) loads. The 66% BM rucksack induced significantly greater oxygen uptake than the 0, 22, and 44% BM ($p < 0.05$). Light rucksack loads (≤ 22% body mass) have a negligible effect on standing metabolic rate that may not be physiologically important. However, heavier rucksack loads (≥ 44% body mass) elicit more pronounced metabolic responses that cannot be overlooked.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Introduction: Soldiers are required to carry loaded rucksacks equipped with supplies for both combat and basic needs. Studies have shown a number of factors can influence energy expenditure during movement with a loaded rucksack. However, there is a lack of quantitative data describing the impact that added load has on an individual's standing metabolic rate. This work assessed the metabolic costs of standing while carrying a set of loads that were fixed percentages of the individual's body mass (BM).

Methods: Fourteen male US Army Soldiers (age 21 ± 2 years; height 174 ± 7 cm; BM 73 ± 10kg) stood for 6 minutes with four different levels of rucksack loading (0, 22, 44, and 66% body mass). Volunteers wore a respirator mask connected to a metabolic cart (ParvoMedics TrueOne 2400; ParvoMedics; Salt Lake City, UT) to collect continuous respiratory measurements. We performed Fisher's least significant difference (LSD) procedure to identify significant differences between loads for three primary metabolic outcomes: oxygen uptake (VO_2), respiratory exchange ratio (RER), and rate of metabolic energy expenditure (EE).

Results: Rucksack load had a significant main effect on VO_2 ($p < 0.000$) resulting in a graded response (0% BM 4.00 ± 0.53 $ml \cdot kg^{-1} \cdot min^{-1}$; 22% BM 4.14 ± 0.56 $ml \cdot kg^{-1} \cdot min^{-1}$, 4.47 ± 0.37 $ml \cdot kg^{-1} \cdot min^{-1}$, 4.80 ± 0.65 $ml \cdot kg^{-1} \cdot min^{-1}$). Similarly, rucksack load also had a significant main effect on EE ($p < 0.000$) and differences between loads (0% BM 1.17 ± 0.16 kcal min^{-1}; 22% BM 1.2 ± 0.16 kcal min^{-1}; 44% BM 1.30 ± 0.11 kcal min^{-1}; 66% BM 1.40 ± 0.19 $kcal \cdot min^{-1}$). There was no significant main effect of load on RER ($p = 0.354$) as values were nearly identical between conditions (0% BM 0.82 ± 0.08; 22% BM 0.80 ± 0.06; 44% BM 0.79 ± 0.06; 66% BM 0.81 ± 0.06).

Conclusion: Light rucksack loads (≤ 22% body mass) have a negligible effect on standing metabolic rate that may not be physiologically important. However, heavier rucksack loads (≥ 44% body mass) elicit more pronounced metabolic responses that cannot be overlooked. Further investigations of the relationship between rucksack load and physical performance decrements during subsequent Warfighter tasks are needed.

INTRODUCTION

Warfighters are required to carry pack loads of equipment and supplies for both battle and their basic needs while in the field (1). Pandolf et al. (2) identified that body mass (BM), load mass, walking speed, type of surface, and grade are the primary factors which influence walking energy expenditure (EE). Accordingly, there are equations to predict the energy costs of walking with and without load (3-6). Still, there are conflicting findings about the metabolic cost of load carriage while standing (2, 7-10).

Pandolf et al. (2) reported that load increases standing metabolic rate as a function of total mass times the square of load-to-body mass ratio. Conversely, four other studies indicate that loads have limited impact on standing metabolic rate (7-10). However, these four studies examined the metabolic effects of light fixed loads and only on small samples of individuals of varying body sizes. From these works and others, Bastien et al. (11) suggested that loads up to 60% BM are either supported by “non-metabolizing tissues” or are too light to significantly increase standing metabolic rate. However, the volume of oxygen uptake (VO_2) increases during other isometric exercises, such as knee extensions (12) and leg presses (13). Consequently, an incremental increase in standing metabolic cost would be expected when carrying a load. Therefore, an independent experiment with a larger sample size and incremental loads scaled as a percentage of BM is necessary to better understand the effect of load on standing EE.

Understanding how heavy loads affect EE while walking and standing provides a critical piece of information needed to make data-driven decisions for mission planning. Knapik et al. (1) found that carrying heavy loads during long-distance runs and short sprints decreased performance, and military marches with load are associated with increased risk of injury. Tenan and colleagues (14) showed that heavy rucksacks impacted a Soldier’s ability to complete subsequent military tasks. Therefore, a better understanding of impact of load on standing EE is of importance to mission planning.

Energy expenditure is most often assessed using indirect calorimetry which requires several variables including VO_2 and expired carbon dioxide (VCO_2). Measures of VO_2 are often used to assess the body’s ability to take in and deliver O_2 and to active tissues as well as the ability of those tissues to utilize available O_2 (15). This measurement quantifies the efficiency of the body to deliver O_2 to working muscles at the cellular level. Therefore, increases in VO_2 are indicative of increased work rate and metabolic requirements during aerobic exercise. Respiratory exchange ratio (RER) is a measure of the relative relationship of CO_2 produced during metabolism to the amount of O_2 utilized during activity (RER = VCO_2/VO_2). Respiratory exchange ratio is often used to indirectly determine the fuel source utilization (16). As the intensity of exercise or work increases, carbohydrates become the dominate fuel, producing more CO_2 and therefore increasing the RER value to between 0.9 and 1.0. Consequently, we chose EE, VO_2, and RER as our study's three primary outcomes for quantifying the effect of load on standing metabolism.

Our specific aim was to clarify the existing ambiguity between load and standing metabolic rate. Specifically, this study provides a quantitative assessment of whether EE increases with incremental rucksack loads (22, 44, and 66% BM) compared to unloaded standing (0% BM). The findings from this study will be used to improve energy expenditure prediction equations and produce more accurate estimates of energy expenditure during complex work. These improved models will, in turn generate higher quality mission planning and risk assessment tools for military, police, firefighting, and manual labor professions.

METHODS

The effect of load on standing metabolic rate was assessed using a randomized, counterbalanced experimental protocol. Volunteers completed five visits over the course of the study, separated by a minimum of at least two recovery days. The first three visits consisted mainly of familiarization procedures while the final two visits incorporated the standing trials. Volunteers completed standing trials with two of the four load conditions (0, 22, 44, and 66% BM) per visit in a randomized order.

Recruitment Methods and Volunteers

Volunteers were recruited through the US Army Natick Soldier Systems Center (NSSC) Human Research Volunteer pool and from active duty personnel stationed at NSSC. This study was approved by the US Army Medical Research and Development Command Institutional Review Board (MRDC IRB) and the Scientific Review Committee at the US Army Research Institute of Environmental Medicine (USARIEM; Natick, MA).

Fourteen male US Army Soldiers, (age 21 ± 2 years; height 174 ± 7 cm; BM 73 ± 10 kg), participated in this study. All volunteers had prior experience carrying heavy loads, were injury-free, not on medical profile, and were in overall good health. All volunteers were briefed of the purpose, risks, and benefits of the study. Prior to study activities, volunteers each provided written informed consent and completed medical screening to ensure they met the appropriate inclusion criteria. During screening, volunteers completed a background questionnaire to obtain demographic, health status, and physical activity information.

Equipment

The Modular Lightweight Load-Carrying Equipment (MOLLE 4000) frame rucksack with a baseline load of 11 kg (25 lbs) was worn for each test. Rucksack fit was adjusted prior to testing, and the same rucksack was carried for each test. Loads were arranged in the rucksack so that the heaviest mass was closest to the body. Load was added using rubber bumper plates and smaller hand/ankle weights. Hard foam was used as needed to stabilize the load.

A stationary metabolic cart (TrueOne 2400, ParvoMedics; Salt Lake City, UT) was used to perform indirect calorimetery. Continual gas measurements were collected to measure VO_2 and VCO_2. Measurements were in turn used for RER and EE assessments. The rate of EE was calculated using the Brockway formula (17). Volunteers were fit-tested to the respiratory mask at the start of each visit. If a volunteer's mask was removed between trials, the fit was re-checked prior to initiation of the next trial.

Test Sessions

Volunteers completed five study visits separated by at least two recovery days each. Included were three familiarization visits and two test visits. During the familiarization visits, volunteers were trained in testing procedures (e.g. inserting a rectal thermometer telemetry pill) to include fit-testing rucksacks and respiratory masks utilized for metabolic cart measurements, overview of questionnaires to be completed, urine sampling, and daily body weights. Visits also included trials carrying each of the three weighted loads set to specific percentages of their BM (22, 44, and 66% respectively). In addition, volunteers completed baseline fitness and body composition assessments including maximum oxygen uptake (VO_{2max}) testing.

Prior to each visit, volunteers were instructed to avoid caffeine, nicotine, and food (>10 hours) and alcohol (> 24 hours). Volunteers were also instructed to avoid vigorous exercise and high-intensity exercise for at least 24 and 48 hours, respectively, before each visit. Volunteers were instructed to wear standard US Army physical training attire (e.g. shorts and t-shirt) each test day, as well as standard issued military boots and socks for military ruck marches. To ensure individuals were hydrated, each volunteer was provided one 500mL water bottle the evening before and the morning of each visit.

Volunteers were assigned a specific arrival time that was consistent throughout the study and ranged from 0600 – 0900. Upon arrival, volunteers completed a daily questionnaire to obtain information about their pre-study compliance (e.g. dietary and physical activity instructions), sleep status, and pain status. To assess hydration status, volunteers were then asked to provide a urine sample that was tested for urine specific gravity. Volunteers were considered properly hydrated when specific gravity was less than or equal to 1.03. Prior to exercise, volunteers were instructed to insert a rectal thermometer telemetry pill for monitoring of core body temperature. Nude and clothed body weights were then measured in triplicate using a stationary scale from behind a privacy screen.

During each test visit, volunteers completed 6-minute trials with two of the four randomly assigned loads while standing and then while walking at four progressively faster speeds (0.45-1.97 $m \cdot s^{-1}$). Volunteers were given a 12-minute rest period between each load trial to ensure there were not any residual effects from the preceding trial. All volunteers completed each of the four loads conditions over the two testing visits.

Statistical Analyses

All data are reported as mean ± SD and were analyzed using Excel statistical software (Microsoft Excel for Office 365, Microsoft Corporation; Redmond, WA). Fisher's least significant difference (LSD) was performed to identify significant differences between loads for three primary metabolic outcomes: VO_2, RER, and EE. If a significant main effect was detected by repeated measures analysis of variance (ANOVA), paired t-tests were used to examine significant difference between loads. The α-level for statistical significance was set to $p \leq 0.05$.

RESULTS

Table 1 displays the minimum, mean ± standard deviation, and maximum loads that were worn during this study. Mean VO_2, RER, and EE for each condition are displayed in Table 2.

Table 1. Minimum, mean, and maximum rucksack loads worn by test volunteers per condition during standing trials.

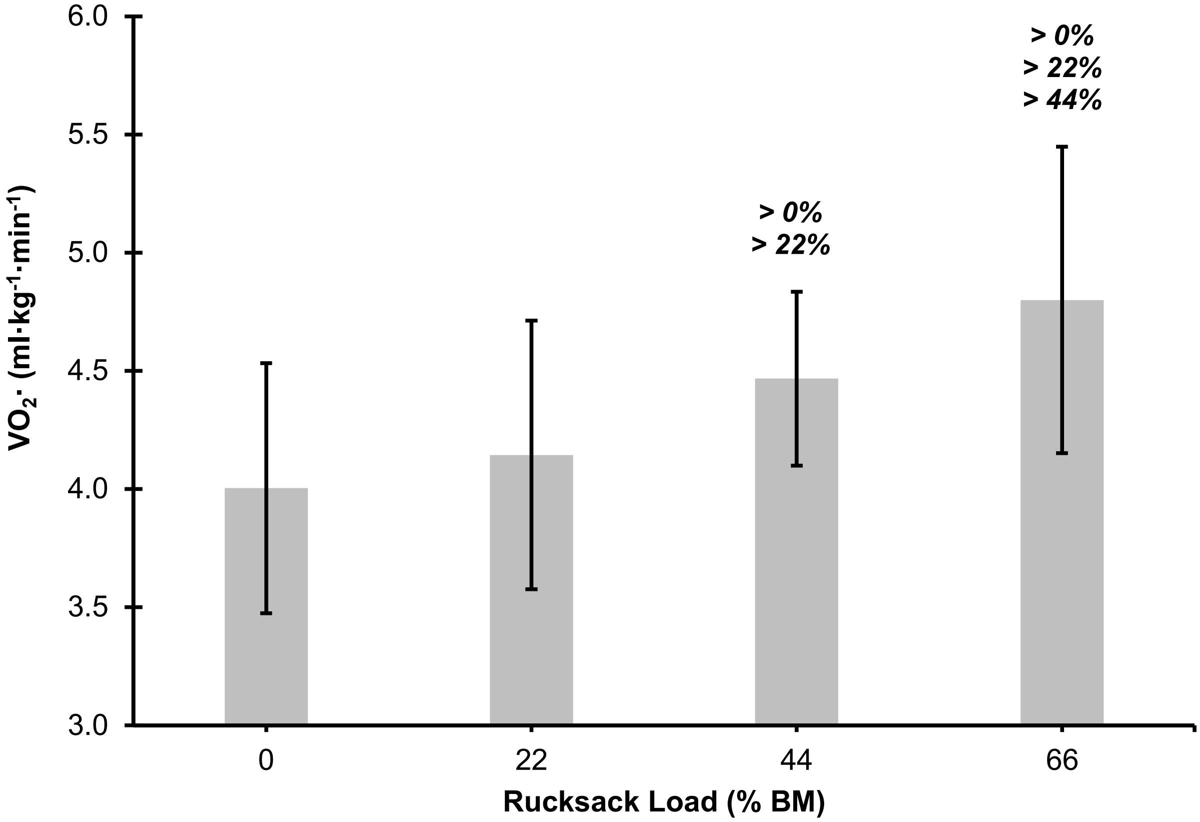
Load (% body mass)	Minimum (kg)	Mean ± SD (kg)	Maximum (kg)
22	12.3	16.2 ± 2.0	20.0
44	24.5	32.3 ± 4.2	39.9
66	36.3	48.5 ± 6.2	59.9

Table 2. Effect of rucksack load on oxygen uptake (VO_2), respiratory exchange ratio (RER), and metabolic energy expenditure (EE) while standing**.**

Load (% body mass)	VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	RER	EE ($kcal \cdot min^{-1}$)
0	4.00 ± 0.53	0.82 ± 0.08	1.17 ± 0.16
22	4.14 ± 0.56	0.80 ± 0.06	1.20 ± 0.16
44	4.47 ± 0.37	0.80 ± 0.06	1.30 ± 0.11
66	4.80 ± 0.65	0.81 ± 0.06	1.40 ± 0.19

Repeated measures ANOVA identified a significant main effect of rucksack load on standing VO_2 ($p < 0.000$). Pairwise t-tests identified significant differences between loads as shown in Figure 1 with mean VO_2 shown across rucksack loads. Oxygen uptake was not significantly different between the 0% and 22% BM loads ($p = 0.294$). However, VO_2 was significantly higher with the 44% BM load versus both 0% BM ($p < 0.000$) and 22% BM ($p = 0.003$) loads. Similarly, the 66% BM rucksack induced significantly greater VO_2 than the 0% BM ($p < 0.000$), 22% BM ($p = 0.001$), and 44% BM ($p = 0.025$) loads. When expressed relative to unloaded standing, VO_2 increased slightly with the 22% BM load (4 ± 13%) but more substantially with 44% BM (13 ± 11%), and 66% BM (20 ± 9%).

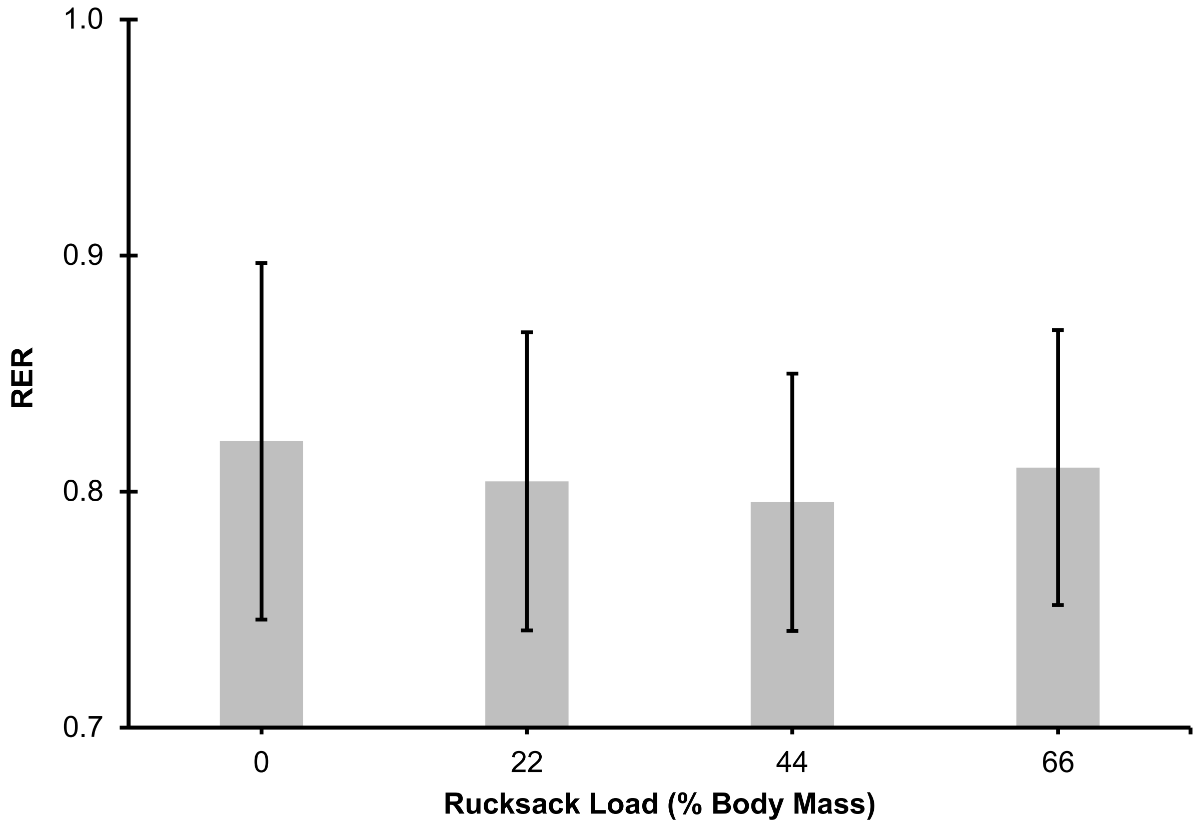
Figure 1. Effect of percentage body mass (BM) rucksack loads on oxygen uptake (VO_2) during standing.



> 0%, significantly greater than 0% BM load condition ($p < 0.05$);
> 22%, significantly greater than 22% BM load condition ($p < 0.05$);
> 44%, significantly greater than 44% BM load condition ($p < 0.05$).

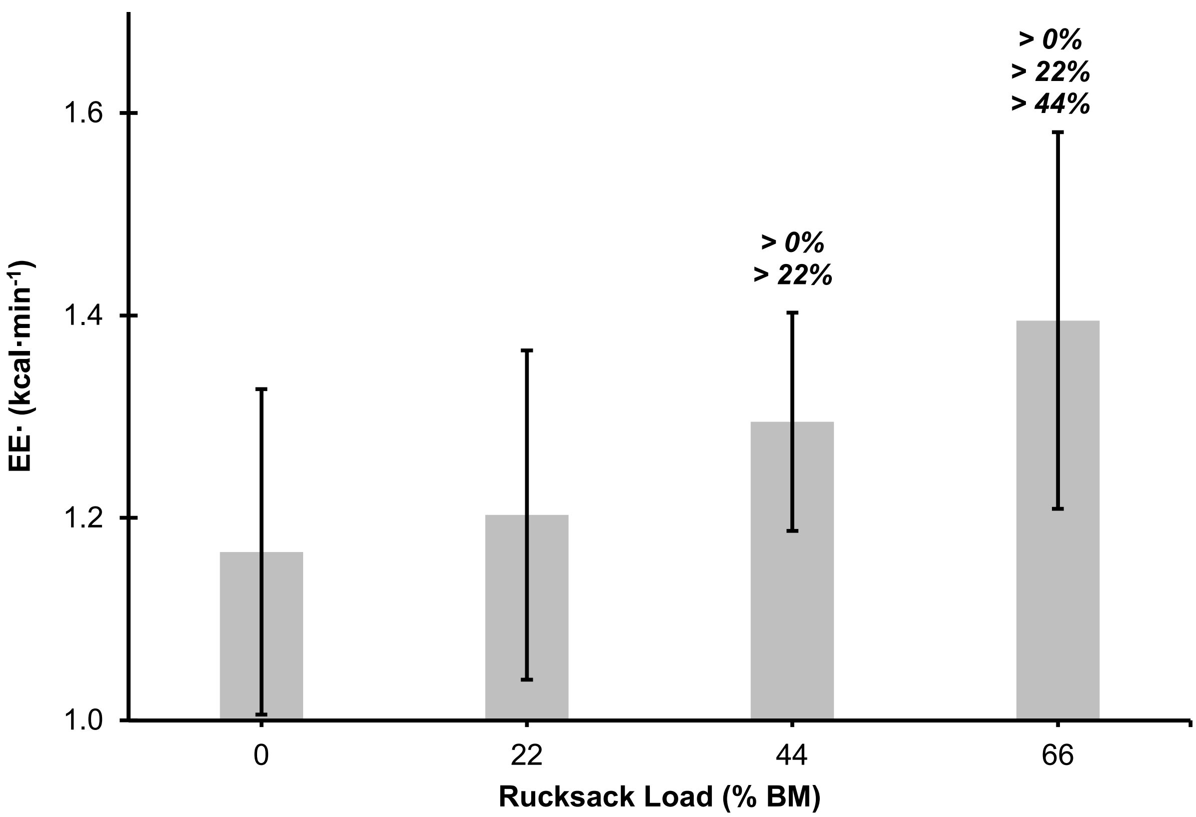
Figure 2 displays the mean RER across each rucksack load. Rucksack load did not have a significant main effect on RER ($p = 0.354$) according to repeated measures ANOVA.

Figure 2. Effect of percentage body mass (BM) rucksack loads on respiratory exchange ratio (RER) during standing.



Repeated measures ANOVA determined a significant main effect of rucksack load on metabolic EE ($p < 0.000$). Energy expenditure was not significantly different between the 0% and 22% BM loads ($p = 0.331$). However, loads greater than or equal to 44% BM showed significant increases in EE from the lower loads. Energy expenditure for 44% BM load was greater than both 0% BM ($p < 0.000$) and 22% BM ($p = 0.002$) loads. Similarly, the 66% BM rucksack induced significantly greater EE than the 0% BM ($p < 0.000$), 22% BM ($p = 0.001$), and 44% BM ($p = 0.017$) loads.

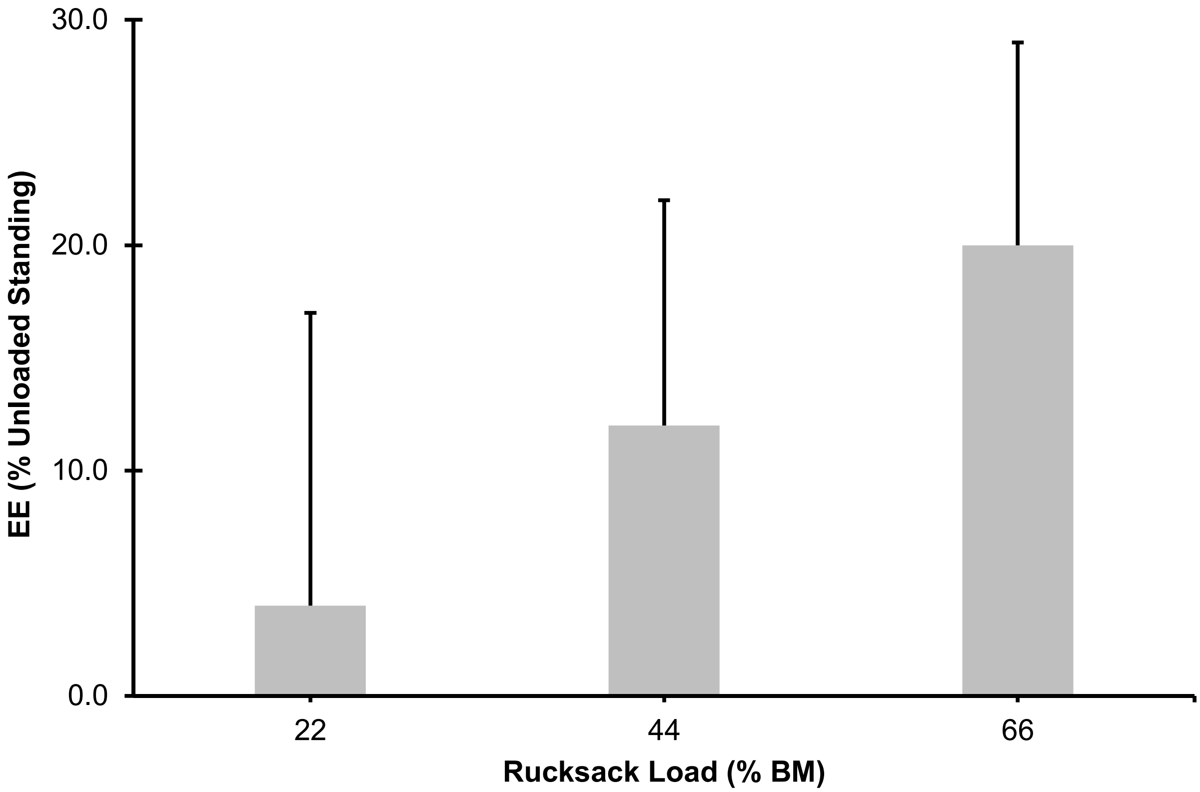
Figure 3. Effect of percentage body mass (BM) rucksack loads on metabolic energy expenditure (EE) during standing.



> 0%, significantly greater than 0% BM load ($p < 0.05$);
> 22%, significantly greater than 22% BM load ($p < 0.05$);
> 44%, significantly greater than 44% BM load ($p < 0.05$).

Figure 4 displays changes in EE relative to unloaded standing. The 22% BM load induced only a small change in EE relative to unloaded standing (4 ± 13%). In contrast, more pronounced EE increases were observed with the 44% BM (12 ± 10%), and 66% BM (20 ± 9%) loads. Notably, the relative changes in EE from unloaded standing predicted by the Pandolf et al. equation (2) for the 22% BM (8%), 44% BM (37%), and 66% BM (96%) loads are much higher than the values recorded during the present study.

Figure 4. Rucksack load induced changes in energy expenditure (ΔEE) relative to unloaded standing.



DISCUSSION

Our study on the effects of incremental rucksack loads on standing metabolism determined that there are statistically significant increases in VO_2 and EE with loads of 44% BM or greater. The difference in metabolic responses between standing with and without light rucksack loads (i.e. ≤ 22% BM) was small and might not be physiologically important. However, this study demonstrated more pronounced metabolic responses to heavier rucksack loading (i.e. ≥ 44% BM) that may add substantially to a Soldier's daily EE if packs are worn for sustained periods of time.

While prior studies on the effect of load on standing EE are conflicting (2, 7-10), our investigation demonstrated increases in VO_2 and EE with the heavier loads (44 and 66% BM). Interestingly, RER remained relatively consistent across all trials, suggesting similar contribution from carbohydrate and fat energy sources during both unloaded and loaded standing. However, the substantial increase in VO_2 and EE for loaded conditions at or above 44% BM indicates a greater overall energy requirement.

Several studies have examined the impact of sustained exercise with or without a loaded rucksack on subsequent performance of Warfighter tasks (1, 14, 18-20). Load mass and distribution of the mass appear to contribute to the impact of prior exercise on military performance (1). There are conflicting findings about the impact of exercise on specific military tasks, such as marksmanship, grenade throwing, and others, independent of load (1, 14, 18, 19). However, no study has investigated how load-induced increases in standing EE relate to subsequent task performance or perception of task difficulty.

An important aspect of Warfighter performance is injury prevention. While increased EE will add to daily energy needs, it may accelerate physical fatigue and compromise motivation or attention (21), which may be contributing to the heightened risk of physical injury observed in those carrying heavy loads. Increased incidence of blisters, stress fractures, foot and knee pain, and shoulder and low back injuries are associated with load carriage (22). Increases in factors that can predispose an individual to risk of injury can also hinder performance over a longer period of time. A better understanding of how standing with increased loads affects Soldier injury and performance will aid in tactical guidance and mission planning related to rest time and pack removal (22).

The muscle fatigue associated with stabilization of loads may be contributing to military injuries. Roy et al. (23) investigated associations between injuries in military populations and potential risk factors such as the time spent standing each day. In a self-reported survey, 579 volunteers from two brigades that recently completed a 12-month deployment to Afghanistan revealed that 13% of the volunteers reported standing 0-4 hours daily, 24% reported standing 5-8 hours, 34% reported standing 9-12 hours, and 29% reported standing for more than 12 hours (23). Notably, Roy et al. (23) found that time spend standing was one of several variables, including load carriage and heavy worn loads, that was associated with increased risk of injury.

While numerous studies have shown that uphill walking increases EE (24), few have investigated whether the effect of load on standing metabolic rate is augmented when standing on an incline (8). Future studies can determine if heavier loads significantly increase EE while standing on an uphill grade. Eccentric muscular work published by Santee et al. (25) found that walking downhill with and without lighter loaded packs may decrease EE, but can be offset by muscular function and other variables. Future investigations may help describe the magnitude to which downhill standing or walking with heavy loads impacts EE and how muscular work may be altered with heavy packs, aiding both the military and civilian population in better understanding energy efficiency during rest and standing positions with heavy loads.

The results of this study emphasize the need to develop loaded standing metabolic rate equations. Accurate metabolic costs are essential for military thermophysiological models such as the Heat Strain Decision Aid (HSDA) (26-27) and the Cold Weather Ensemble Decision Aid (CoWEDA) (28) since errors will compound over time. Although military populations are the primary focus application for these findings, other load-carrying populations, such as hikers, may benefit from knowledge of the change in VO_2 and EE directly related to standing with heavy loads for short periods of time. Hikers focused on energy efficiency will be able to make better informed decision if their backpack mass is greater than 44% of their own BM. Hikers should include options of pack removal while determining their route or during prolonged rest periods.

Conclusions

The current investigation provides clarification to the mixed findings about the impact of heavy load carriage on standing metabolic rate. Our study provides evidence that standing metabolic rate increases with heavy rucksack loads (> 44% BM). Rucksack mass directly impacts EE, which may cause changes in behavior, ultimately impacting mission performance and injury prevention. Further work and education are needed to provide guidance for military and other recreational load carrying populations. In striving for optimal performance, it is important that all changes in performance variables are understood to help determine best courses of action.

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