The Physiology and Biomechanics of Load Carriage Performance

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ABSTRACT Introduction: The weight that soldiers are required to carry in training and in combat has continually increased over the years. Changes in load carried or pace of activity will alter the physiological and biomechanical stress associated with the activity. Whether it is part of the soldier's training or an actual operation, managing the proper load and speed to minimize fatigue can be integral to the soldier's success. Without a proper understanding of the multitude of factors that may affect load carriage performance, mission success may be jeopardized. The purpose of this review is to summarize and clarify the findings of load carriage research and to propose a new method for analyzing the intensity of load carriage tasks, the Load–Speed Index. Materials and Methods: We reviewed studies that examined military load carriage at walking speeds and included articles that featured non-military participants as deemed necessary. Results: Major factors that can affect load carriage performance, such as speed of movement, load carried, load placement, body armor, and environmental extremes all influence the soldier's energy expenditure. A critical aspect of load carriage performance is determining the appropriate combination of speed and load that will maximize efficiency of the activity. At the higher end of walking speeds, the walk-to-run transition represents a potential problem of efficiency, as it may vary on an individual or population basis. Conclusions: This review provides a comprehensive overview of these factors and suggests a new Load–Speed Index, which can be utilized to define thresholds for load and speed combinations and contribute to the understanding of the physiological and biomechanical demands of load carriage marches. The literature recommends that load and speed should be managed in order to maintain an exercise intensity ~45% VO_2 max to delay time to fatigue during prolonged marches, and the Load–Speed Index corroborated this finding, identifying 47% VO_2 max as a threshold above which intensity increases at a greater rate with increases in load and speed. The Load–Speed Index requires validation as a predictive tool. There are no definitive findings as to how load affects the speed at which the walk-to-run transition occurs, as no investigations have specifically examined this interaction. Additional research is clearly needed by examining a wide range of loads that will facilitate a clearer understanding of speed and load combinations that optimize marching pace and reduce energy expenditure.

INTRODUCTION

Load carriage is a crucial aspect of a soldier's physiological performance during many military operations.[1] Managing the proper load and speed to minimize fatigue can be integral to mission success. A historical perspective of military load carriage reveals a linear increase in load weight over time.[2] This is significant because there have been casualties and major operational inefficiencies due to mismanagement of the load carried into combat.[2] Post-WWII more attention in the U.S. Army has been paid to the effects of load and load carriage guidelines. Load echeloning is the fundamental approach to the problem, with combat loads defined as the minimum essential equipment necessary for the current situation.[1] The three subdivisions of combat loads are fighting load (direct contact with enemy), approach march load (fighting load plus minimum equipment for sustained fighting), and emergency approach march load (equipment that must be carried by soldiers as a last resort due to lack of vehicle ability or terrain issues). Recommendations regarding fighting loads have been defined as 30% of body weight (BW) or 22 kg, and approach march loads as 45%BW or 33 kg.[3] In a recent, updated report these loads were increased; fighting loads ranging from 27 to 36 kg (30% BW), approach march loads ranging from 36 to 45 kg (45% BW), and emergency approach loads ranging from 45 to 57 kg (46–70%BW).[1] These new guidelines were similar to data collected from light infantry-brigade operations in Afghanistan in 2003, in which average fighting loads of 29 kg and approach march loads of 46 kg were reported.[4]

The increase in absolute load (kg) but maintenance of relative load (%BW) in the recent U.S. Army guidelines[1] reflects the increase in BW of American soldiers. The average height and body mass of soldiers have increased concomitantly from 171 cm, 64 kg in 1864 during the Civil War[5] to 178 cm, 83 kg during Operation Enduring Freedom in 2005[6] (BMI increase from 21.9 to 26.2). Increases in both load carried into combat, and soldier's body mass, places the current infantry soldier in a situation in which the management of energy expenditure (EE) via cardiorespiratory and biomechanical efficiency are paramount. In addition, the load being carried during extreme environmental temperatures can significantly increase EE[7] and lower time to

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fatigue.[8] With longer duration operations (actual mission or training), muscle injury and acute overuse symptoms may be more of a limiting factor than the physiological capability if cardiorespiratory workload is maintained at a low level.[9] One of the purposes of this review is to delineate the threshold at which the cardiorespiratory system becomes a limiting factor in load carriage performance. Another purpose is to examine the interactions of speed and load with special attention to their effect on task duration and on the walk-to-run transition (WRT) during load carriage.

BIOMECHANICS OF LOAD CARRIAGE

Gait Variability

The primary aspect of biomechanics that has been studied in conjunction with marching with a load is gait variability.[2,10–14] When carrying a load, individuals adjust their stride rate, stride length, and speed, employing a gait pattern that attempts to maximize efficiency and minimize EE.[15] The manipulation of any of these factors will inherently affect all three parameters.[16] Changes in gait pattern resulting from an increase in load increase metabolic cost and reduce the capacity for prolonged duration marches.[15,17,18]

Numerous investigators have examined the effect of load carriage on the spatiotemporal parameters of gait. When marching pace was self-selected, loads up to 18 kg (approximately 27% BW) produced a non-significant increase in stride length, stride rate, and speed.[14] In contrast, others have reported that loads less than 16 kg (approximately 21%BW) did significantly increase all three parameters.[10] Increases with lighter carriage loads may be due to an over-compensation effect; soldiers may be subconsciously attempting to maintain their speed by increasing their stride length and stride rate, which ultimately results in a faster walking speed.[10,14] Loads >16 kg (>21% BW) significantly decreased all parameters, which decreased speed.[10] The 21% BW load threshold for significant changes in gait pattern is lower than the 30%BW fighting load defined by the U.S. Army[1], revealing the importance of keeping loads below this threshold for optimal mechanical efficiency.

Fixed-pace studies have also examined the effect of load on the interaction between stride rate and stride length. As load carried increases, stride length decreases to provide greater stability.[12,19] Therefore, at a fixed speed, stride rate would need to increase in order to maintain a consistent pace.[12,13,20] Two investigations have demonstrated that as load increases, a significant decrease in stride length was compensated by a significant increase in stride rate, with loads ranging from 9 to 37 kg (14–56%BW) to maintain a fixed speed of 6.4 km h^{-1},[20] and with loads ranging from 6 to 47 kg (8–61%BW) at speeds ranging from 3.9 to 5.4 km h^{-1}.[12] Increasing load carriage during fixed-pace marches alters gait patterns and increases EE.[18] Although height and leg length account for stride length variability, gait pattern is not always significantly affected because of other factors such as; force, angles, and flexibility.[21]

Military Load Placement

Multiple studies have examined the effects of load placement via a backpack, double pack, head basket, head strap, hip belt, and trunk vest.[2,22,23] Due to the nature of military tasks, the only appropriate way to carry a load is via backpack or double pack because they allow versatility while also keeping the load close to the body's center of gravity.[24] Carrying a load close to the body's center of gravity reduces biomechanical alterations and has the lowest EE of any arrangement.[23] While the double pack causes fewer deviations in gait, it inhibits movement of the torso and arms, making the backpack the most ergonomic form of military load carriage.[10,13,22,25]

The U.S. Army employs two types of backpacks, the All-Purpose Lightweight Individual-Carrying Equipment (ALICE) pack and the Modular Lightweight Load-Carrying Equipment (MOLLE) pack, both of which allow loads to be placed in different locations within the pack.[2] A low load creates more stability, but causes a more drastic forward lean which further distorts the gait pattern.[26,27] However, proper upright posture is more sustainable with higher load placement, ultimately resulting in lower EE, making high placement preferable for managing fatigue.[26–29]

Effects of Essential Military Equipment on EE

Mechanical obstruction of the lungs due to thoracic load placement affects the cardiorespiratory system's ability to endure prolonged activity. Tight body armor and a backpack chest strap mechanically limits the lungs' ability to expand to their full capacity, limiting tidal volume and thereby reducing maximal working capacity and increasing oxygen cost during submaximal tasks.[30,31] In addition, when the respiratory muscles fatigue as a result of mechanical restriction (metaboreflex), this can lead to vasoconstriction of lower body muscles and peripheral fatigue, increasing heart rate (HR), and blood pressure.[30,32–34] With a given load, wearing body armor may increase oxygen consumption more than backpack carriage.[35] Body armor weighing 10 kg (approximately 16%BW) has been reported to cause a 12–17% increase in VO_2 compared with no load,[35] whereas 15%BW increase in backpack load increased metabolic cost by 5–6%.[36] At a given HR, ratings of perceived exertion were higher with body armor weighing 10 kg (16%BW) than with no load,[35] potentially pointing to a mechanism in which breathing is more constricted with body armor than with no load or equivalent backpack load. An additional investigation reported that pulmonary ventilation increased exponentially once participants reached an intensity eliciting 75% of their VO_2max, suggesting a physiological threshold may be induced by thoracic restriction from the body armor.[37]

Loads carried on the extremities have also been studied. Due to their placement far from the center of gravity, military boots increase EE 7–10% for every kg of weight added.[38–40] The weight of military boots range from 0.5 to 1 kg per boot and inhibit movement of the ankle joint, alter natural gait patterns and increase metabolic cost.[38–40] Carrying a load on the thigh has a minimal effect on gait (i.e., ~4% increase in EE per kg), due to its position closer to the center of gravity.[40,41] Change in EE is not significant when carrying a 4.4 kg rifle in the hands, but there is an inhibition in natural arm swing movement which may become more of a factor only with faster speeds.[42]

PHYSIOLOGY OF LOAD CARRIAGE

Energy Expenditure

The effect of load carriage on EE has been studied extensively. Predictive models of the physiological demands of the soldier enable commanders to optimally manage the compounding stresses that soldiers encounter.[43] Accurate predictions of EE help commanders to set optimal work: rest ratios, understand nutritional needs, and design efficacious training programs.[44] EE predictions are especially helpful when mission planning expediency is key.[45]

The Pandolf equation published in 1977 was an important attempt to predict EE based on BW, load, speed, grade, and terrain.[46] At grades up to 30% and loads ranging from 0 to 30 kg (approximately 0–43%BW), the equation was accurate at 4.0 km h^{-1} but significantly underestimated EE at 2.4 km h^{-1}.[47] With level treadmill walking and at the same loads (0–43% BW), the equation underestimated metabolic rate by 14–33% at both speeds.[47] In contrast, with loads ranging from 4.1 to 37.4 kg (approximately 6–54%BW) at grades of 0 and 6%, EE of walking at 6 km h^{-1} did not differ significantly from predicted values.[48] Recently, Drain et al[49] assessed the equation's validity with different combinations of equipment and a wide range of speeds. Soldiers walked with 22.7 and 38.4 kg (26% and 45%BW) at three-speed designations: walking (2.5–3.5 km h^{-1}), approach march (4.5–5.5 km h^{-1}), and movement while engaged (6.5 km h^{-1}). The Pandolf equation significantly underestimated EE for all three conditions, especially at the slowest pace; 32–33% at 2.5 km h^{-1}. The Pandolf equation may be more accurate at speeds above 2.4 km h^{-1}, which is the average marching pace for U.S. infantry during the day across cross-country terrain.[1]

A major consideration when examining the cardiorespiratory effects of load carriage and EE predictions from short duration protocols is the phenomenon of HR and VO_2 drift. Predictions are based on a steady state being reached, thus they underestimate metabolic work during high duration, highly fatiguing tasks. HR and VO_2 drift occur in prolonged marches of various speeds (3.96–6.5 km h^{-1}), loads (25–49.4 kg) and duration (2–3 h), even when the initial intensity is low (e.g., 30% VO_2max).[50,51] For instance, the Pandolf equation underestimated EE 9–18% during a 12 km treadmill march.[51] In another study, VO_2 and HR increased significantly every 15 minutes up to completion of a 1-hour walking protocol at 5.4 km h^{-1} with 55%BW.[52] The load selected for that study was done to replicate the 56.7% average approach marching load used by Army light infantry teams in Afghanistan in 2003.[4] Comparisons between the initial 15 minutes to 1 hour of marching revealed a significant increase in both HR and % VO_2 max (12.6% and 10.3%, respectively). The higher cardiorespiratory output occurring alongside an increase in neuromuscular fatigue appeared to support previous research suggesting that an altered muscle recruitment pattern is indicative of fatigue with a load carriage.[53] A study by Epstein and colleagues[54] reported that at the completion of a 2-hour walking protocol at 4.5 km h^{-1}, participants had an 8.8% increase in VO_2max compared with baseline while carrying a 40 kg load (approximately 60%BW). However, when those soldiers carried a load of 25 kg (approximately 37%BW) no cardiovascular drift was noted. This difference can be attributed to both load and duration, as the difference between conditions only appeared 100 minutes into the protocol.

Interaction of Speed, Load, Intensity, and Duration

The soldier's capacity to carry a heavy load into a military operation without substantial fatigue is multifaceted, and is highly related to the soldier's relative aerobic intensity (%VO_2max) and the duration of the task.[55] It is important to understand the interaction between intensity and duration to minimize fatigue. As duration of activity increases, the intensity of exercise that can be sustained is reduced. Similarly, higher intensity exercise also results in a shorted time to exhaustion. During a march, VO_2 is largely a function of speed and load carried. As speed and load increase, there is an elevation in HR, oxygen uptake, EE, blood lactate concentrations, and ventilatory rate.[17,37,45,46,50,56–58] With loads ranging from 4.4 to 40 kg (approximately 7–61%BW), Pal and colleagues[59] reported very strong correlations ($r = 0.97–0.99$) between load and %VO_2max at speeds of 3.5 and 4.5 km h^{-1}. In another study examining the interaction between load and intensity, each additional kg of load increased oxygen uptake by 33.5 mL min^{-1}, HR by 1.1 bpm and pulmonary ventilation by 0.6 L min^{-1} for participants maintaining a constant workload of 25% and 50% VO_2max.[37] Quesada and colleagues[36] reported that at the end of a 40-minute march (6 km h^{-1}), a significant linear increase was noted in VO_2 (30%, 36%, and 41%) with increasing loads (0, 15% BW and 30% BW, respectively).

To prevent fatigue and sustain exercise, it is recommended that tasks be performed at or below 50% of one's VO_2max.[60] When physical activity is performed at higher intensities anaerobic metabolism is elevated, leading to an earlier onset of fatigue. One study requiring participants to walk on a treadmill at 3 km h^{-1}, reported time to exhaustion to significantly decrease from 40.9 to 17.7 minutes as load carriage increased from 72.5 to 93.3 kg (approximately 90–115%BW).[61] This substantial drop in time to exhaustion occurred at 54.9 ± 4.8% VO_2 max. Investigations of unloaded walking/running and cycling reported a curvilinear relationship between relative intensity and time to fatigue, with a possible threshold above ~45% VO_2max.[45,55,62,63] U.S. Army guidelines, likewise, suggest that the relationship between endurance capacity of load carriage tasks and EE are curvilinear.[1,45] During self-paced marches between 1 and 3.5 hours in duration, participants limited their speed and therefore EE in order to maintain an aerobic output of less than 45% VO_2max, independent of load carried.[64,65] Similarly, when soldiers marched 204 km over 6 days, they maintained an intensity equating to 30–40% of their VO_2max.[66] Supporting these findings, Epstein and colleagues[54] reported that cardiovascular drift occurred at a workload that elicited an aerobic output of 52% VO_2max, but not at 46% VO_2max. Present U.S. Army guidelines list marches as totaling 20–32 km day^{-1}, which equates to a maximum duration of 5–10 hours per 24-hour period on road or 8–20 hours on cross-country terrain.[1] Controlling the intensity of the march to limit soldiers from exceeding ~45% of their VO_2max appears to delay the onset of fatigue during extended duration, loaded marches.

Aerobic intensity, and therefore duration, is greatly affected by the interaction between load and speed. To maintain an intensity of march equating to 35% VO_2max, the maximal load and speed combinations were reported to be 55%BW at 3.5 km h^{-1} and 32%BW at 4.5 km h^{-1}.[59] Another study, examining 16 different combinations of load and speed, reported the maximal speed and load combination to maintain relative VO_2 <50% to be: 3.5 km h^{-1} with 50 kg (approximately 73%BW), 4.5 km h^{-1} with 35 kg (approximately 51%BW), and 5.5 km h^{-1} with 20 kg (approximately 29%BW).[56] These results should be taken into consideration when planning a military mission, by prioritizing speed, load or distance and adjusting the other variables accordingly.[19,56,61]

Environmental Stress and Load Carriage Ensembles

Marching with a load in either the heat or cold will have an additive effect on the stress of the activity and must be accounted for in mission planning or training.[31,67] This becomes further magnified when the environmental stress is combined with high levels of fatigue and a nutritional deficit.[68] When marching in the heat, the increase in sweat rate results in further strain on blood volume, which is already being diverted to working skeletal muscle.[67] Increase in cardiovascular strain lowers central blood volume, potentially leading to a hypotensive response, syncope, or heat exhaustion.[67] One of the mechanisms of body cooling involves evaporative heat loss, however, load carriage gear and uniforms obstruct effective evaporative cooling causing an insulatory effect.[68]

Substantial increases in sweat loss during exercise in the heat lead to dehydration, which accelerates the rise in core body temperature and lowers task duration.[68] When wearing full and partial protective ensembles during a walking protocol, heat exhaustion occurs at body temperatures ranging between 38.8 and 39.2°C for 75% of participants.[69] Caldwell and colleagues[8] examined the interaction between load and cardiovascular strain in soldiers marching in an ambient temperature of 36°C with 60% relative humidity with loads of 2.05 kg (approximately 3%BW) and 9.41 kg (approximately 12%BW) at 2.0 and 4.0 km h^{-1}. The 12% BW load significantly augmented the rise in core temperature from 0.37°C per hour to 0.51°C per hour (38% faster), and significantly decreased predicted time to reach theoretical HR threshold of 180bpm from 5 hours and 45 minutes to 4 hours and 10 minutes. In addition, the 12%BW load caused significantly greater sweat loss than the 3% BW load (1.74 kg vs. 1.32 kg) over the 2.5-hour protocol. In another study, walking in 40°C compared with 20°C temperature increased time to complete a 5-km march significantly more than carrying loads of 20, 30, or 50%BW compared with carrying no weight.[70] Marching in the heat will exacerbate the effects of dehydration, creating a higher relative intensity for a given workload and reducing time to exhaustion.[71]

Cold weather represents a different physiological challenge during load carriage. The increase in EE during military operations in the cold is often due to changes in terrain and added layers of clothing and equipment.[7,72] Controlled studies have also been conducted to isolate the effect of cold temperature. There is uncertainty as to the exact range of temperatures that negatively affect VO_2max, but cold weather appears to attenuate maximal aerobic capacity.[68] VO_2max was significantly lower at −20°C compared with 20°C, but no differences were noted between −10°C and 20°C.[73] Hinde and colleagues[74] studied the interaction between load and cold weather by comparing no load to 18.2 kg (approximately 26% BW) while marching at 4 km h^{-1} in temperatures ranging from −10 to 20°C. During the march, the relative intensity of activity was 24% higher at −10°C, and 22% higher at −5°C when compared to the intensity of exercise performed at 20°C. These changes were consistent regardless of load. However, load carriage had a greater increase on oxygen utilization during a subsequent unloaded bout only in the coldest conditions of −5 and −10°C, revealing an additive effect of load carriage and cold weather on cardiorespiratory output.

THE WRT WITH LOAD

Successfully executing a mission may require soldiers to carry a load at a quicker pace than normally recommended. As walking pace increases, there is a crossover point called the WRT[75], which requires high mechanical energy output.[76] Combat effectiveness and survivability may depend not only on minimizing fatigue during long-duration walking but also during the approach to battlefield. This phase may require a faster speed than distance marches, and this speed may occur slightly higher or lower than the WRT,[49,77] making this an important area of research.

There is a scarcity of research examining the biomechanics and physiology of the WRT with load. In a study examining volunteers with fitness levels comparable to army recruits, some participants were able to jog an entire 3.2-km simulated approach march with 32 kg (approximately 39% BW) while some participants walked, with average speeds ranging from 7.7 to 9.1 km h^{-1}.[77] In an investigation examining elite soldiers carrying a 20 kg (approximately 26% BW) load, some of the soldiers transitioned to running, while others maintained a walking gait at 8.4 km h^{-1}.[57] This is a slightly higher pace than the 7.04–8 km h^{-1} reported as the WRT for non-military populations for unloaded walking,[75,76,78–80] with most investigations reporting a pace closer to 7.2 km h^{-1}.[81] It is unclear if the load, or the advanced training status of the soldiers, accounts for this discrepancy. Interestingly, at 8.4 km h^{-1} the soldiers who transitioned to a running pace presented a lowered physiological response (blood lactate, HR, minute ventilation) than those who chose to maintain a walking pace.[57] This revealed a true metabolic crossover point, in which walking at speeds higher than the WRT, or conversely running at speeds slower than the WRT result in higher EE. However, there is overwhelming evidence that during unloaded walking, participants tend to transition from walking to running at a slower speed than is metabolically optimal, but rather transition at a speed that has a lower rate of perceived exertion, possibly due to lower muscle activation requirements via the engagement of the stretch-shortening cycle during running.[81,82] Further research is needed to understand how load affects the physiological factors of the WRT.

Development of the Load–Speed Index

To clarify the interactions among load, speed, and O_2 consumption, we compiled data from studies that reported load, speed, and VO_2 measured during steady state, treadmill marches. Six investigations of loaded marches are included in the analysis.[51,56,59,61,83,84] All six studies used a fixed pace, with the bulk of the external load in each investigation being carried in a backpack. There were slight differences in the manner of weight distribution, but the investigators of each study attempted to place the weights as close to the center of gravity as possible, to minimize effects of load placement on biomechanics and EE.

Pearson's product moment correlation coefficients were calculated to assess the relationship between the independent variables and % VO_2max. There was a significant positive correlation with % VO_2max for both speed ($r = 0.787$, $p < 0.001$) and load ($r = 0.623$, $p < 0.001$). The product of load (% BW) and speed (km h^{-1}) for a given trial is defined as the Load–Speed Index, calculated using the following equation:

$$\text{Load–Speed Index} = \text{Speed (km h}^{-1}) \cdot \text{Load (\% BW)}$$

Linear regression analysis was then used to determine the correlation between Load–Speed Index and %VO_2max. A significant correlation was found between Load–Speed Index and %VO_2 max ($r = 0.932$, $F = 408.4$, $p < 0.001$) and analysis produced the following regression equation: y(%VO_2 max) = 0.119 × (Load–Speed Index) + 19.851. The Load–Speed Index accounted for 86.8% (r^2) of the variance in % VO_2max. Next, spline regression analysis was used to define threshold values at which there was a change in the slope of the regression line of the relationship between %VO_2max and the Load–Speed index. A significant threshold for change in slope was found at Load–Speed Index of 260 ($p = 0.004$), which corresponded to 47% VO_2max (see Fig. 1). About 47% VO_2max is very similar to ~45% VO_2max reported in the literature as the threshold above which time to fatigue decreases and cardiovascular drift increases.[45,54,64,65]

Using 47% VO_2max as the threshold, we can predict the walking speed that can be employed with a given load in an effort to maintain cardiovascular efficiency for high duration tasks (see Table I for calculations for standard U.S. Army loads[1]).

Finally, speed and load were tested independently for threshold values in relation to %VO_2max by using spline

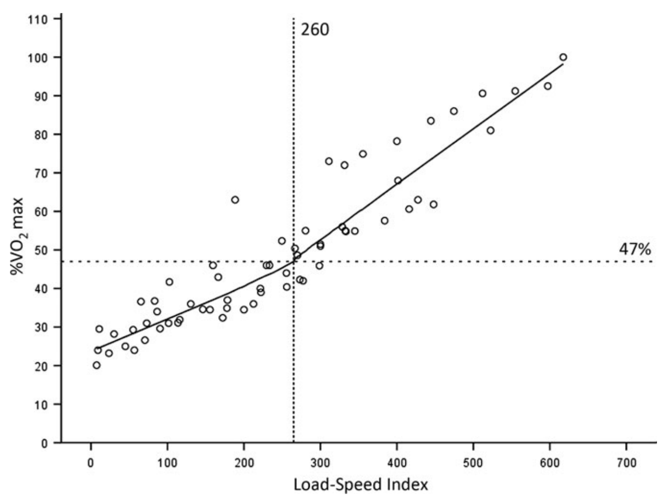

FIGURE 1. The relationship between Load–Speed Index and % VO_2max. Spline regression analysis was used to define thresholds values for % VO_2max related to Load–Speed Index. Spline regression analysis revealed a significant change in the slope of the line ($p = 0.004$) at the Load–Speed Index of 260 and 47% VO_2max.

TABLE I. Maximal Walking Speeds

Type of Load	% BW	Speed (km h^{-1})
Fighting	30	7.60
Approach march	45	5.07
Emergency approach	70	3.26

Maximal walking speeds corresponding to an aerobic output of 47% VO_2max at three standard loads established by the U.S. Army.[1] Speeds were calculated based on the linear regression equation Y (% VO_2max) = 0.119X (Load–Speed index) + 19.851. % BW = Percent body weight.

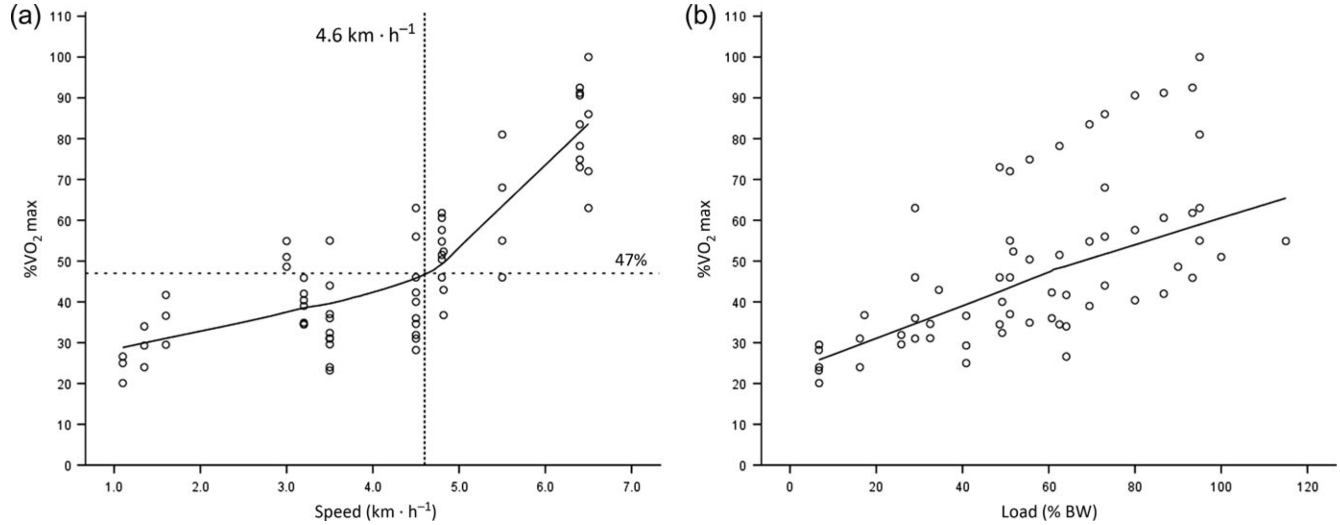

FIGURE 2. Spline regression analysis for %VO_2 and (a) speed (km h^{-1}); (b) load (%BW). Spline regression analysis revealed significant change in the slope of the line ($p < 0.001$) at the speed of 4.6 km h^{-1} and 47% VO_2max, and no significant threshold for load ($p = 0.832$).

regression analysis (Fig. 2). A significant threshold for the change in slope was found at the speed of 4.6 km h^{-1} ($p < 0.001$), corresponding to the same value of 47% VO_2max discovered by the Load–Speed Index spline regression analysis. There was no significant threshold for load based on the spline regression ($p = 0.832$). This is consistent with the consensus from several investigations that an increase in speed has more of an effect on EE, HR and VO_2 than an increase in the load carried.[45,59]

SUMMARY

The soldier's load has been increasing steadily through history, creating a need for a better understanding of the effect of load on a host of biomechanical and physiological variables. EE during loaded carriage is an important aspect in determining the physiological demands on the soldier. The load carried and speed of the march are primarily responsible for changes in EE, and there is much evidence that load and speed should be managed in order to maintain an exercise intensity ~45% VO_2max to delay time to fatigue during prolonged marches.[45,64–66] The Load–Speed Index may be a useful tool for predicting aerobic energy requirements of a march with a given speed and load, or for determining the maximal speed and load that will produce a desired level of exertion. In addition to load and speed, there are a host of additional factors that can influence load carriage performance, such as environmental extremes, body armor, load placement, and the WRT. As such, we also recommend that effort be made in examining flexible/lighter body armor, and the potential impact it may have in enhancing WRT, while maintaining soldier safety. In conclusion, there are no definitive findings as to how load affects the speed at which the WRT occurs, as no investigations have specifically examined this interaction. Additional research is clearly needed by examining a wide range of loads that will facilitate a clearer understanding of speed and load combinations that optimize marching pace and reduce EE.

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