

Soldier Load Carriage: Historical, Physiological, Biomechanical, and Medical Aspects

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This study reviews historical and biomedical aspects of soldier load carriage. Before the 18th century, foot soldiers seldom carried more than 15 kg while on the march, but loads have progressively risen since then. This load increase is presumably due to the weight of weapons and equipment that incorporate new technologies to increase protection, firepower, communications, and mobility. Research shows that locating the load center of mass as close as possible to the body center of mass results in the lowest energy cost and tends to keep the body in an upright position similar to unloaded walking. Loads carried on other parts of the body result in higher energy expenditures: each kilogram added to the foot increases energy expenditure 7% to 10%; each kilogram added to the thigh increases energy expenditure 4%. Hip belts on rucksacks should be used whenever possible as they reduce pressure on the shoulders and increase comfort. Low or mid-back load placement might be preferable on uneven terrain but high load placement may be best for even terrain. In some tactical situations, combat load carts can be used, and these can considerably reduce energy expenditure and improve performance. Physical training that includes aerobic exercise, resistance training targeted at specific muscle groups, and regular road marching can considerably improve road marching speed and efficiency. The energy cost of walking with backpack loads increases progressively with increases in weight carried, body mass, walking speed, or grade; type of terrain also influences energy cost. Predictive equations have been developed, but these may not be accurate for prolonged load carriage. Common injuries associated with prolonged load carriage include foot blisters, stress fractures, back strains, metatarsalgia, rucksack palsy, and knee pain. Load carriage can be facilitated by lightening loads, improving load distribution, optimizing load-carriage equipment, and taking preventive action to reduce the incidence of injury.

Introduction

Soldiers are often required to carry equipment and supplies on their body during military training and operations. Depending on the characteristics of the load, carriage on some parts of body can be more comfortable or efficient than carriage on other parts of the body. Load-carriage systems like backpacks,

shoulder straps, and belts can enhance comfort and efficiency if these systems are designed with an understanding of the general principles and problems associated with human load carriage. Well-designed carriage systems can enhance the likelihood of mission accomplishment by reducing localized stress and fatigue, thus minimizing performance decrements and injuries. A lack of understanding of load-carriage principles and/or the use of inadequate or badly designed carriage systems can have harsh consequences. Military historians cite numerous examples in which heavy loads directly or indirectly resulted in reduced performance, unnecessary deaths, and disastrous engagements.¹⁻⁶

The purpose of this study is to provide an overview of the published research on the historical, physiological, biomechanical, and medical aspects of soldier load carriage. General principles and problems of load carriage are discussed rather than the specific load-carriage systems. Practical, evidenced-based suggestions are offered for reducing the strain of loads on soldiers through equipment modifications, physical training, consideration of biomechanical/physiological principles, and the prevention and treatment of load-carriage-related injuries.

Historical Perspective

Figure 1 shows estimated loads carried by various military units through the ages with emphasis on more recent times. Until about the 18th century, troops carried loads that seldom exceeded 15 kg while they marched. Extra equipment and subsistence items were often moved by auxiliary transport including assistants, horses, carts, and camp followers. After the 18th century, auxiliary transport was de-emphasized, and more disciplined armies required troops to carry their own loads. Modern soldiers often carry a considerable amount of equipment and supplies while on the march, some of which they remove if they come into contact with hostile forces.^{7-10,12-14}

There have been a number of recorded efforts to study and improve soldier mobility beginning with the British efforts after the Crimean War. These efforts generally focused on either (1) determining an acceptable soldier load based on soldier physical capability and/or operational necessity^{2,4,15-19} or (2) developing specialized load-carriage systems.^{2,4,19-21}

In 1987, the U.S. Army Development and Employment Agency¹⁹ proposed five approaches for improving soldier mobility. The first approach was to develop components lighter in weight. However, technical developments were expected to reduce loads only by 6% overall.²² The second approach was the soldier load-planning model. This was a computer program that aided commanders in tailoring loads through a risk analysis based on the mission, enemy, terrain, troops, and time. The third approach was the development of specialized load-carrying equipment. This included such things as handcarts and all-terrain vehicles.

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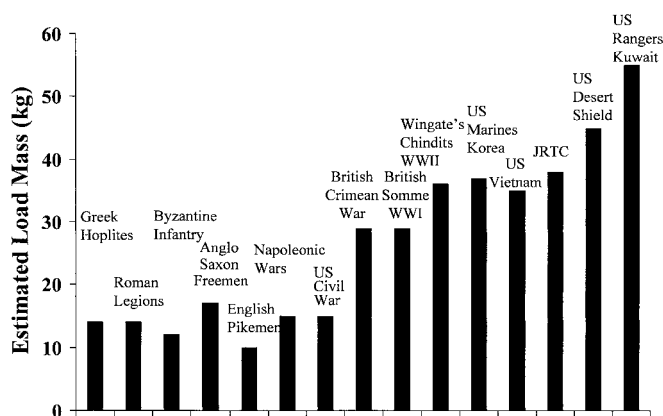


Fig. 1. Loads carried on the march by various infantry units throughout history.⁷⁻¹¹ JRTC, Joint Readiness Training Center (Fort Chaffee, Arkansas, unpublished data).

The fourth approach was a re-evaluation of current doctrine that might affect load carriage. An example of this was an increased emphasis on marksmanship to reduce ammunition loads. The fifth and final approach was the development of special physical training programs to condition soldiers to develop more physical capability for load carriage.

Historical changes in soldier physical characteristics may be important^{13,23} because larger soldiers may be able to carry heavier loads by virtue of greater bone and muscle mass.²⁴ It has been estimated that humans have increased approximately 10 cm in height since the industrial revolution, possibly because of better nutrition.²⁵ Table I provides a summary of the heights and weights of various groups of soldiers and recruits derived from a variety of sources. Before the British Crimean War, only minimum standards are available. U.S. samples show a progressive increase in height and weight since the Civil War. The increase in weight may be attributed to an increase in both estimated fat-free mass and body fat.^{26,27}

Physiological and Biomechanical Aspects of Load Carriage

Historical information indicates that the problems of load carriage have been with us for a considerable time. Physiological and biomechanical research conducted more recently has resulted in the development of general principles, but studies do not reveal a single "best" way of carrying loads that applies to all situations. However, improving load distribution across the body, use of combat load carts, and physical training have been demonstrated to improve soldier mobility.

Load Distribution

There are many ways to carry loads, and the technique the soldier will use depends on the characteristics of the load (size, shape, mass, etc.), how far the load may be carried, previous experience, and the equipment available to the soldier.³¹ Figure 2 illustrates techniques of carrying loads on the upper body that have been directly investigated.³²⁻³⁹

Backpacks and Double Packs

The location of the load on the body will affect both energy cost and gait mechanics. Loads can be transported with the

TABLE I
PHYSICAL CHARACTERISTICS OF VARIOUS GROUPS OF SOLDIERS AND RECRUITS

| | Height (cm) | Body Mass (kg) |
|---|-------------|----------------|
| French samples | | |
| French (Crimean War) ² | 163 | 56 |
| French (post World War I) ² | 163 | NA |
| British samples | | |
| British (post World War I) ² | 168 | 59 |
| British recruits (1978) ²⁸ | 175 | 70 |
| British infantry (1976) ²⁸ | 175 | 73 |
| U.S. samples | | |
| U.S. soldiers (1864) ²⁶ | 171 | 64 |
| U.S. soldiers (1919) ²⁶ | 172 | 66 |
| U.S. soldiers (1946) ²⁶ | 174 | 70 |
| U.S. male soldiers (1978) ²⁷ | 174 | 71 |
| U.S. male soldiers (1984) ²⁹ | 174 | 76 |
| U.S. male recruits (1986) ³⁰ | 175 | 71 |
| U.S. male soldiers, three groups (1986) ³⁰ | 175-176 | 69-77 |
| U.S. male recruits (1998) ^c | 177 | 79 |

NA, Not available.

lowest energy cost (i.e., most efficiently) when they are carried on the head.^{37,40} However, this method is impractical for military operations because it requires a very long training time to use effectively, is useful only in unobstructed horizontal terrain, and produces a high profile (greater body signature).

A more practical choice for military operations is to carry a load as close as possible horizontally to the center of mass of the body.^{41,42} In this regard, the backpack and double pack (half the load carried on the front of the body and half on the back) methods have been shown to be associated with a lower energy cost than most other forms of load carriage in many^{32,34,43-45} but not all^{31,46} studies. The double pack produces fewer deviations from normal walking than does a backpack, including less forward lean of the trunk.⁴⁷⁻⁴⁹ With the double pack, increasing load produces a reduction in stride length and increase in stride frequency, which may be more desirable because it may reduce stress on the bones of the foot. In contrast, with a backpack, there is mixed evidence as to whether stride length lengthens or shortens as the weight carried increases.^{47,50,51}

Double packs can be useful in some military situations (e.g., medics carrying their aid bags on the front of their bodies) but also imposes major limitations for many types of operations. The double pack can inhibit movement and may limit the field of vision in front of the body, making it difficult to see obstructions and traps. Double packs can be burdensome to don and doff; doffing can be very important if sudden or unexpected enemy contact occurs. The double pack can also induce ventilatory impairments³⁶ and greater heat stress symptoms^{46,52} when compared with the backpack. The double pack may restrict tasks such as firing weapons and donning protective masks.

Load-carriage system designers can take advantage of what has been learned from the double pack by distributing the load more evenly over the torso.⁵³ Although it is difficult or almost impossible to make the load equal on the front and back of the body, load-carriage systems could allow a part of the load to be moved forward by the use of load-carrying trunk vests and hip

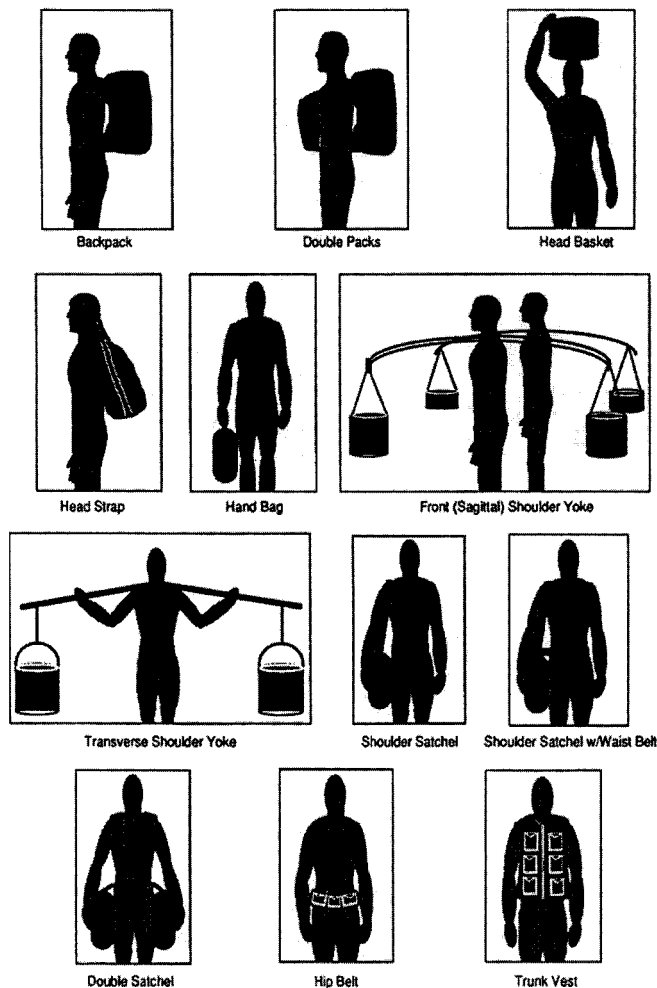


Fig. 2. Methods of load carriage.

belts (see Fig. 2). Items included in the frontal load could optimally consist of equipment the soldier may need quickly or may need often. Moving a part of the load to the front may be expected to reduce energy cost, improve body posture, and reduce injuries.

Pack Frames and Hip Belts

Pack frames and hip belts reduce shoulder stress. The shoulder straps of a rucksack exert pressure on the skin, which can be measured with transducers under the straps. Shoulder pressure is considerably less with a pack frame affixed to a wide, securely fastened hip belt than a pack frame without a hip belt. In one study, 10 kg carried in a frameless pack resulted in a peak pressure of 203 mm Hg; the same mass carried in a pack with a frame and wide hip belt resulted in a peak pressure of only 15 mm Hg. The pack with the frame and hip belt also produced less electromyographic activity in the trapezius muscle, suggesting reduced muscular effort in the shoulder area.⁵⁴ There is some suggestion that experienced individuals adjust their walking posture to reduce forces and force fluctuations in the shoulder straps.⁵⁵

Internal frame packs have supporting structures (usually metal) inside the fabric of the pack and keep the pack closer to

the center of mass of the body; external frame packs have the supporting structure on the outside of the pack, and the pack is usually farther away from the center of mass of the body. There is conflicting information as to whether the internal frame pack has a lower energy cost than the external frame pack.^{56,57} There is no difference in perceived exertion between external and internal frame packs when walking on the level, even terrain;⁵⁶ however, perceived exertion over rough terrain is lower with the internal frame pack.⁵⁸

The design of the pack system influences subjective reports of discomfort. For backpacks with and without frames, the majority of discomfort appears to be in the neck and shoulder region. For a backpack with a hip belt, discomfort is localized to the mid-trunk and upper legs.³⁶ Overall, when the load is carried primarily on the waist through use of a hip belt, there is less subjective discomfort compared with shoulder load carriage.⁵⁹ When walking uphill, individuals give higher ratings for balance and ease of gait for packs with hip belts that pivot in the sagittal plane.⁶⁰

Placement of the Load in the Backpack

The location of the load in the pack may affect energy cost and influence body mechanics. In one study, higher energy costs were associated with a load that was lower in the pack and farther away from the body; lower energy costs were associated with loads placed higher in the pack and closer to the body (Fig. 3).⁶¹ However, another study using almost identical methods found no difference in energy cost with similar load placements.⁴⁶

Both high and low load placements bring about forward body lean, but this effect is greater for low placements. This is because the lower load requires more forward body rotation about the hips or ankles to bring the pack center of mass over the feet.^{46,62} The additional forward body rotation tends to bring the body's center of mass over the front half of the foot, which could increase the likelihood of foot strain and injury. However, placement of the load high in the pack tends to destabilize posture to a greater extent than lower placements, especially among tall men, as measured by the amount of body sway while standing with the load.⁶³ Dynamic moments are approximately 40% greater with the high-back placement, an affect attributed to the greater rotational inertia of the high load.⁶⁴

These data suggest that a low or mid-back load placement might be preferable for stability on uneven terrain, particularly during unexpected stumbles where high-load placement can necessitate relatively high-muscle forces to maintain postural

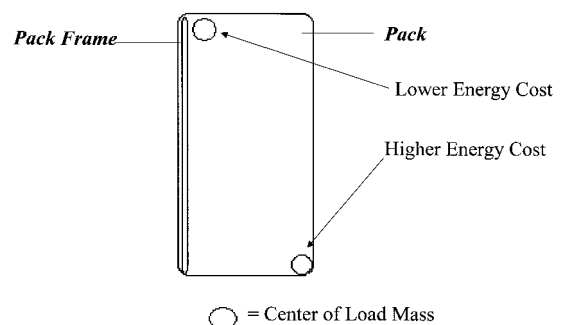


Fig. 3. Effect of placement of the load in the backpack on energy cost.⁶¹

stability. The high load placement may be best for even terrain because it minimizes energy cost and keeps body posture with a load most similar to that without a load.^{62,65} Soldiers walking on level terrain subjectively prefer a higher load placement.⁴⁶

Load Carriage on the Feet, Thighs, and in the Hands

Loads can be carried in places other than the torso, although other body positions result in a higher energy expenditure. Loads carried on the feet result in an energy cost five to seven times higher than an equivalent load carried on the upper body.^{42,66} For each kilogram added to the foot, the increase in energy expenditure is 7% to 10%.^{42,66–68} This suggests that footwear should be as light as possible, compatible with durability requirements.

Loads carried on the thigh result in energy costs lower than foot carriage but greater than torso carriage. For each kilogram added to the thighs (at approximately mid-thigh level), the increase in energy cost is approximately 4%.^{69,70} Compared with the feet, less mechanical work is performed when load masses are carried on the thighs because the rotational inertia of a body segment about a joint is greatly affected by the distance from the joint to the center of mass of the segment. Because a mass on the thigh is much closer to the hip than is a mass on the foot, the thigh mass offers less resistance to rotation about the hip than does the foot mass. Thus, changes in gait with increasing thigh loads are minimal.⁶⁹

Similarly, carriage of loads in the hands results in a higher energy cost than carriage on the torso^{34,43,71} and produces greater cardiovascular strain.^{71,72} Hand carriage is more efficient than foot carriage because the energy cost of carrying loads on the ankles exceeds that of carrying loads in the hands by five to six times if the hand load is carried close to the body.⁴² This is likely related to the fact that leg swing is an essential part of walking, whereas arm swing is a secondary aspect of gait that can be greatly reduced without affecting walking speed.

Strap Adjustments

Although not tested experimentally, it is reasonable to assume that shifting loads from one part of the body to another during a march can improve soldier comfort and allow loads to be carried for longer periods of time. Load shifting is accomplished with some pack systems using various strap adjustments. Strap adjustments may redistribute the load to other muscles or other portions of previously loaded muscles. They also allow local body areas to “recover” from the pressure of the load.

Some rucksacks have “sternum straps” that are attached horizontally across both shoulder straps at mid-chest level. When the sternum strap is tightened, it pulls the shoulder straps toward the midline of the body so that pressure is shifted from more lateral to more medial segments of the body. When the sternum strap is loosened, the shoulder straps move laterally, and the load is shifted to more lateral portions of the shoulder.

Most pack systems with hip belts and shoulder straps have adjustments that allow more of the load to be placed on the hips or shoulders. When the shoulder strap tension is reduced (straps loosened), more of the load is placed on the hips. With the shoulder straps tighter, more of the load is placed on the

shoulders. Other strap adjustments that shift load pressures, center the pack, and improve lumbar support can further improve soldier mobility and comfort.⁶⁰

Load Carriage Using Carts

Military personnel seldom consider using carts to transport loads, but for some missions this may be an option. Positive and negative aspects emerged in a field trial of three combat load carts. On the positive side, the tested carts were generally durable, and were effectively used in flat terrain, in barrier construction, and in resupply. On the negative side, the carts created problems in rugged terrain; they were noisy in brush or rocky areas thus reducing tactical surprise, and equipment could get caught in the wheels of some carts.⁷³

A combat load cart appropriate for military operations should have a low center of gravity, a wide wheel base, and a large wheel size.^{74,75} Compared with body carriage, energy cost was reduced by 88% when a 50-kg load was pushed in a cart on a smooth surface.⁷⁴ Pulled carts (rather than pushed) appear to be easier to control on uneven terrain and also result in considerable energy cost savings.⁷⁵

A specially designed combat load cart that was pulled by soldiers using a hip belt resulted in faster march speeds than moving the same loads with a rucksack. Over mixed terrain (paved road, dirt road, field, and rough trail), 34- and 61-kg loads were moved 22% and 44% faster over a 3.2-km distance.⁷⁶ This combat load cart, specifically developed for military operations, is available in the U.S. Army.

Physical Training and Load Carriage

Appropriately designed physical training is another method of increasing soldier mobility. Walking with backpack loads over a period of weeks results in a decrease in the energy cost of carrying the load.⁷⁷ Australian military recruits with high initial aerobic capacity (predicted $\text{VO}_{2\text{max}} = 51 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) further improved their aerobic fitness by engaging in regular backpack load carriage. Loads were progressively increased during an 11-week basic training program, and improvements in aerobic capacity were similar to those of a control group performing the traditional recruit training program involving running.⁷⁸

Twelve-week physical training programs, involving a combination of aerobic training (running) and resistance training (weight lifting), improved the speed at which military men completed a 3.2-km distance carrying 46 kg⁷⁹ and the speed at which military women completed a 5-km distance carrying 19 kg⁸⁰ even when these load carriage tasks were not included in the training program. Interestingly, neither running nor resistance training alone improved march speed,⁷⁹ suggesting that both types of training must be performed to improve road marching capability. When regular road marching with loads (at least twice a month) was included in a program that also involved running and resistance training, soldiers marched faster than if march training was not included.⁸¹ Substantial improvements in load carrying performance were found when civilian women were trained with a combination of resistance training, running, and load carrying.⁸²

Sex Differences

Compared with men, women walk with shorter stride length and greater stride frequency. As loads increase, the women's

stride length decreases whereas that of the men does not show significant change. With increasing load, women also show a more pronounced linear increase in the time both feet are on the ground (double support time) than do men. Difference between men and women persist even when differences in body size and body composition are taken into account.⁸³ When men and women were asked to stand with internal and external frame packs, 9 of 10 men preferred the internal frame whereas 8 of 10 women preferred the external frame.⁶²

When men and women were asked to complete a 10-km road march as quickly as possible carrying loads of 18, 27, and 36 kg, men were approximately 21% faster, regardless of load. On questionnaires, women commented more often than the men that the pack straps were uncomfortable, hip belts ill fitting, and rucksacks unstable. An independent predictor of march time (when sex was included in the equation) was acromial breadth (shoulder breadth). Because pack systems have been designed primarily based on the anthropometry of men, these data suggest that if consideration is given to the anthropometry of women in military pack systems, the march speed gap between men and women may decrease.^{84,85}

Factors Involved in the Energy Cost of Load Carriage

Studies conducted on treadmills for short periods of time show that energy cost increases in a systematic manner with increases in body mass, load mass, velocity, and/or grade.⁸⁶⁻⁹⁰ Type of terrain also influences energy cost, as shown in Figure 4.^{75,91,92} Pandolf et al.⁹³ expanded on the work of Givoni and Goldman⁹⁴ to develop an equation to predict the energy cost of load carriage: $M_w = 1.5 \times W + 2.0 \times (W + L) \times (L/W)^2 + T \times (W + L) \times (1.5 \times V^2 + 0.35 \times V \times G)$, where M_w is the metabolic cost of walking (watts), W is body mass (kg), L is load mass (kg), T is terrain factor (1.0, black top road; 1.1, dirt road; 1.2, light brush; 1.5, heavy brush; 1.8, swampy bog; 2.1, loose sand; [terrain factor for snow is dependent on depth of the depression: $T = 1.30 + 0.082 \times D$, where D = depression depth in centimeters],⁹¹ V is the velocity or walk rate (m/s), and G is slope or grade (%).

The Pandolf equation has been independently validated using a range of loads and body masses.⁹⁵ However, the equation has several limitations. First, it does not accurately predict the energy cost of downhill walking.^{96,97} Downhill walking energy cost approximates a U-shape when plotted against grade: it initially decreases and then begins to increase.⁹⁸⁻¹⁰⁰ The lowest energy cost appears to occur between -5% and -15%, depending on individual gait characteristics.^{45,98,100} Recently Santee et al.¹⁰⁰

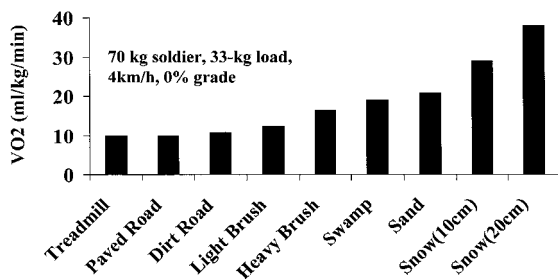


Fig. 4. Influence of terrain on the estimated energy cost of backpack load carriage.⁹¹⁻⁹³ Numbers after the snow estimates are the depth of depression the shoe makes in the snow.

developed an empirical model to predict the energy cost of downhill walking. The model assumes that the initial reduction in downhill walking energy cost is due to the negative work of gravity but that this is reduced by the eccentric action of the muscles to decelerate the body and energy absorbed by the muscles and joints. The equation is: $W_{td} = W_1 + (2.4 (m_t \times g \times h \times s^{-1}) \times 0.3^{\alpha/7.65})$, where W_{td} is the total metabolic cost (watts), W_1 is metabolic cost of level walking (W), m_t is total load mass (kilograms), g is acceleration due to gravity (9.8 m/s²), $h \times s^{-1}$ is vertical displacement (m) in 1 second, and α is the grade or slope for negative work.

A second limitation of the Pandolf equation may be the fact that it may not account for increases in energy cost over time. In studies used to develop the equation, energy cost was examined for short periods, usually less than 30 minutes. Some studies^{101,102} have shown that, at higher loads and/or speeds, the energy cost of prolonged (>2 hours) load carriage at constant speed increases over time. Another study did not find an increase in energy cost after approximately 4 hours of walking.¹⁰³ There were differences in the type of backpacks used in these studies. The studies showing the increase in energy cost used a pack that placed loads primarily on the shoulder; the study not finding the increase in energy cost used a pack with a hip belt that placed much of the load on the hips. Whether energy expenditure increases over time is important because the individual carrying the load may become more easily fatigued if energy cost does increase.

Medical Problems Associated with Load Carriage

Injuries associated with load carriage, although generally minor, can adversely affect an individual's mobility and thus reduce the effectiveness of an entire military unit. Tables II and III show the results of two studies that recorded acute injuries during military road marching operations.^{104,105} Foot blisters, back problems, and metatarsalgia were the most common march-related injuries. Table IV provides a summary of these and other common load-carriage-related injuries with their signs, symptoms, prevention, and treatment.

Foot Blisters

Foot blisters are the most common load-carriage-related injury.¹⁰⁴⁻¹⁰⁷ Blisters can occur when slight movements of the foot in the footwear produce frictional shear forces on the skin. Some portions of the footwear exert more pressure on the skin than other portions. If the foot movements produce enough shear cycles at these pressure points and if the pressure is great enough, a blister will result.¹⁰⁸ Blisters can cause extreme discomfort, may prevent soldiers from completing marches, and can lead to many days of limited activity.^{104-106,109} Especially in field conditions, if blisters are not properly managed, they can progress to more serious problems such as cellulitis or sepsis.^{109,110}

Heavy loads have been shown to increase blister incidence,^{84,111,112} possibly by increasing pressure on the skin and causing more movement of the foot inside the boot through higher propulsive and breaking forces.^{48,49} Other blister risk factors include tobacco use, low aerobic fitness, and ethnicity.^{105,113,114}

TABLE II
INJURIES AMONG 335 INFANTRY SOLDIER DURING A 20-km MAXIMAL EFFORT ROAD MARCH¹⁰⁴

| Injury | During March ^a | | 1–12 Days Postmarch ^b (n) | Totals | |
|------------------|---------------------------|-------------------------------|--|--------|-----|
| | Continued March (n) | Did Not Continue March (n) | | N | % |
| Foot blisters | 16 | 0 | 19 | 35 | 38 |
| Back pain/strain | 5 | 7 | 9 | 21 | 23 |
| Metatarsalgia | 1 | 1 | 9 | 11 | 12 |
| Leg strain/pain | 0 | 0 | 7 | 7 | 8 |
| Sprains | 1 | 1 | 4 | 6 | 7 |
| Knee pain | 0 | 0 | 4 | 4 | 4 |
| Foot contusion | 0 | 1 | 1 | 2 | 2 |
| Other | 1 | 2 | 2 | 5 | 5 |
| Total | 24 | 12 | 55 | 91 | 100 |

^a From medics and physician during the march.

^b From medical records after the march.

TABLE III
INJURIES AMONG 218 INFANTRY SOLDIERS DURING A 5-DAY, 161-km ROAD MARCH¹⁰⁵

| Injury | During March ^a | | 1–15 Days Postmarch ^b (n) | Totals | |
|------------------|---------------------------|-------------------------------|--|--------|-----|
| | Continued March (n) | Did Not Continue March (n) | | N | % |
| Foot blisters | 43 | 3 | 3 | 49 | 48 |
| Metatarsalgia | 8 | 2 | 9 | 19 | 19 |
| Back pain/strain | 4 | 1 | 1 | 6 | 6 |
| Sprains | 2 | 3 | 0 | 5 | 5 |
| Knee pain | 3 | 1 | 3 | 7 | 7 |
| Ingrown toenail | 0 | 3 | 0 | 3 | 3 |
| Stress fracture | 0 | 1 | 0 | 1 | 1 |
| Other | 8 | 3 | 1 | 12 | 12 |
| Total | 68 | 17 | 17 | 102 | 100 |

^a From physician's assistants at fixed medical sites along the march.

^b From medical records after the march.

When loads are very heavy (61 kg), the double pack has been shown to result in less likelihood of blisters than the back-pack,⁵³ suggesting that better load distribution can reduce blisters. Spenco shoe insoles have also been shown to reduce foot blister incidence, possibly because they absorb some frictional forces in anteroposterior and mediolateral directions.^{115–117} Regular physical training with load carriage may induce skin adaptations that reduce the probability of blisters.¹⁰⁸ Blisters may thus be less of a problem in units that march regularly. However, sudden increases in march intensity or distance will probably make blisters more likely, regardless of training regularity.

Moist skin increases frictional forces and probably increases the likelihood of blisters.^{108,109,118} Acrylic socks decrease the number and size of blisters among runners,¹¹⁹ possibly by conducting sweat away from the foot.¹²⁰ A nylon sock worn inside a wool sock reduces the incidence of blisters among soldiers who are road marching.^{121,122} A polyester sock worn inside a very thick wool-polypropylene sock reduced blister incidence during Marine recruit training.¹²³ It is reasonable to assume that changing wet socks for dry ones may also reduce foot blisters.

Antiperspirants also reduce foot sweating^{124,125} and the incidence of foot blisters. A 20% solution of aluminum chloride hexahydrate in an anhydrous ethyl alcohol base was effective in reducing the likelihood of march-related blisters if the prepara-

tion was applied to the entire foot for at least three nights before a march.¹²⁶ Once the antiperspirant effect has been achieved, it may be maintained with applications once per week.¹²⁷ However, many individuals report irritant dermatitis using this preparation,¹²⁶ which may require the application of a topical steroid. Possible ways of reducing irritant dermatitis include using a lower concentration preparation, changing the treatment schedule (same number of applications but over a longer period of time), or discontinuing use. Antiperspirants in emollient bases are not effective in reducing blisters, presumably because emollients interfere with the antiperspirant effect.¹²⁸

Low Back Injuries

The site of a low back injury is difficult to identify because the pain may result from trauma to a variety of structures including spinal discs, the ligaments connecting the vertebral bodies, nerve roots, or supporting musculature.¹²⁹ Injuries of this type pose a significant problem during load carriage. In one study,¹⁰⁴ 50% of the soldiers who were unable to complete a strenuous 20-km walk reported problems associated with the back. Dalen et al.¹³⁰ reported frequent problems with back strains during a 20- to 26-km walk. However, another study¹⁰⁵ reported only a 3% low-back injury incidence and few associated days of limited duty after a 161-km road march.

TABLE IV

SUMMARY OF COMMON LOAD CARRIAGE-RELATED INJURIES WITH PREVENTION AND TREATMENT STRATEGIES (SEE TEXT FOR FULL DESCRIPTIONS AND APPLICATIONS)^{108,129}

| Injury | Signs and Symptoms | Prevention | Treatment |
|------------------|---|--|---|
| Foot blisters | Elevated area, lighter in color than surrounding skin, and filled with fluid. Pain, burning, warmth, erythema | 1. Acrylic, nylon, or polyester inner sock; thick, snug, dense weave outer sock with inner sock 2. Spenco insoles 3. Antiperspirants 4. Load distribution more evenly around body center of mass 5. Reduce load mass 6. Precondition feet through physical training and road march practice 7. Improve aerobic fitness 8. Smoking/tobacco cessation | Intact blister: drain, leave top in place, light pressure dressing. Torn blister: remove top, antibiotic ointment, surgical bandage. Hydrogel or hydrocolloid dressings; polyurethane films |
| Metatarsalgia | Pain, swelling on sole of foot | 1. Precondition feet through physical training and road march practice 2. Reduce load mass | RICE ^a Anti-inflammatory medication ^b |
| Stress fractures | Persistent, bony pain, well-circumscribed palpable area of bony tenderness | 1. Smoking/tobacco cessation 2. Precondition feet and legs through physical training and road march practice | RICE ^a Anti-inflammatory medication ^b |
| Knee pain | Pain, swelling, crepitus, instability | Lower extremity strengthening and stretching | RICE ^a Anti-inflammatory medication ^b |
| Low-back pain | Pain, muscle spasm, neurological symptoms | 1. Load distribution more evenly around body center of mass 2. Reduce load mass 3. Trunk and abdominal strengthening | RICE ^a Anti-inflammatory medication ^b |
| Rucksack palsy | Upper extremity numbness, paralysis, cramping; scapular winging | 1. Framed rucksack 2. Use of hip belt on rucksack 3. Load shifting using strap adjustments | RICE ^a Anti-inflammatory medication ^b |

^a RICE, Rest, ice, compression, elevation.^b Anti-inflammatory medication, aspirin or a nonsteroidal anti-inflammatory.

Heavy loads may be a risk factor for back injuries.¹¹¹ This could be because heavier loads lead to more forward trunk inclination¹³¹⁻¹³⁴ that increase the torque on the lower back that the back muscles must resist. It is also possible that heavier loads do not move in synchrony with the trunk,^{133,135} causing cyclic stress of the back muscles, ligaments, and spine.^{132,133} It has been suggested that the double pack may help reduce the incidence of back problems because it results in a more normal posture and eliminates prolonged forward inclination of the trunk.⁴⁸ Thus, better load distribution could reduce back injuries. Also, a general overall strengthening and warm-up program involving the back, abdomen, hamstrings, and hip muscles may assist in prevention of back injuries.¹²⁹

Metatarsalgia

Metatarsalgia is a descriptive term for nonspecific painful overuse injury of the foot. The usual symptom is localized tenderness on the sole of the foot under the second or third metatarsal head. Sutton¹³⁶ reported a 20% incidence of metatarsalgia during a strenuous 7-month Airborne Ranger physical training program that included regular load carriage. Another study reported a 9% incidence after a 5-day, 161-km road march with soldiers carrying an average load of 47 kg.¹⁰⁵ One study¹⁰⁴ reported a 3% incidence after a single strenuous 20-km walk with soldiers carrying 45 kg. These data suggest metatarsalgia incidence increases with more exposure to load-carriage tasks.

Metatarsalgia is sometimes associated with foot strain caused by rapid changes in the intensity of weight-bearing activity.¹²⁶ Walking with heavy loads may be a predisposing factor for metatarsalgia because this may cause the foot to rotate anterior-posteriorly around the distal ends of the metatarsal bones for more prolonged periods of time, resulting in more mechanical stress in this area.⁴⁸

Stress Fractures

Lower extremity stress fractures are common in military recruits¹³⁷⁻¹⁴² and have also been reported in trained soldiers.¹⁴² During the Central Burma campaign in World War II, 60 stress fracture cases were reported in one infantry unit during a 483-km road march.¹⁴³

Stress fractures are attributable to repetitive overloading of bones. In response to repetitive stress such as road marching, bone tissue remodels. The resorption of bone occurs before new bone formation, and thus bone tissue is temporarily weakened and more susceptible to injury.¹⁴² The most common areas of involvement are the metatarsals, tibia, and calcaneus,¹⁴³⁻¹⁵⁰ although many other lower extremity sites can be involved.¹⁴² When the metatarsals are involved, bony pain can be elicited by compression, and pain is generally localized on the dorsal side of the metatarsals, which can distinguish the pain from metatarsalgia.

Demonstrated risk factors for stress fractures in military

recruits include female sex,^{137,142} Caucasian ethnicity, age,^{137,150,151} taller body stature,¹⁴⁰ prior physical inactivity,^{140,150-152} cigarette smoking,^{151,153} amenorrhea,^{150,153} high alcohol use,¹⁵¹ and bone geometry.¹⁵⁴ Other factors that may increase risk include load-carriage distance^{142,147} and walking style.^{140,155}

Knee Pain

Knee pain is another condition that has been associated with load carriage. Dalen et al.¹³⁰ reported a 15% incidence (17 of 114 cases) of knee pain during their load-carriage study. Knapik et al.¹⁰⁴ reported only a 1% incidence of knee pain (2 cases of 335 soldiers) after a 20-km march, but the two cases resulted in a total of 14 days of limited duty. Reynolds et al.¹⁰⁵ found a 3% incidence of knee pain (7 cases from 218 soldiers) after a 161-km march.

Various disorders that may be involved in knee pain include patellofemoral pain syndrome, patellar tendinitis, bursitis, and ligamentous strain. These conditions can arise from an abrupt increase in road marching mileage or intensity or from climbing hills if soldiers have not been conditioned for this. Quadriceps and hamstring strengthening may be important for the prevention of recurrence.¹⁵⁶

Rucksack Palsy

Rucksack palsy is a disabling injury and has been widely reported in association with load carriage.^{136,157-161} It is hypothesized that the shoulder straps of a backpack can cause a traction injury of the C5 and C6 nerve roots of the upper brachial plexus. In minor cases, compression results in entrapment of the long thoracic nerve. Symptoms include numbness, paralysis, cramping, and minor pain in the shoulder girdle, elbow flexors, and wrist extensors. Long thoracic nerve injuries usually present with "scapular winging" because of weakness of the serratus anterior muscle. Sensorimotor deficits from rucksack palsy injuries are usually temporary but, in some cases, may result in a chronic condition. Nerve conduction studies and electromyographic studies may be necessary to document this condition.^{157,161}

Use of a frame and hip belt has been demonstrated to reduce the incidence of rucksack palsy,¹⁵⁷ presumably by reducing pressure on the shoulders.⁵⁴ Hypothetical risk factors for rucksack palsy include heavy loads, load distribution, and longer carriage distances.^{111,157}

Load Carriage and Performance of Other Tasks

A significant consideration from a military perspective is how well soldiers are able to perform military tasks during load carriage. The mass, volume, and distribution of the load appear to be important variables. As the mass increases, there are systematic decrements in the performance of tasks such as long-distance runs, short sprints, agility runs, ladder climbs, and obstacle course traversals.^{59,90,162,163} The decrement in performance of some tasks (long-distance runs, jumping, short sprints, obstacle course traversals) is estimated at approximately 1% to 3% per kilogram load.^{59,90,164} Loads of greater volume inhibit movement under obstacles. Loads distributed around the body center of mass (waist) result in more effective

task performance than backpack loads.⁵⁹ Sex differences in load carriage are also apparent with women having more difficulty than men in climbing walls (presumably due to shorter stature and lower muscle strength) and less accurate than men in throwing grenades.¹⁶³

In some operations, soldiers are required to walk long distances and perform critical military tasks at the completion of the march. Very strenuous marches (maximal speed with loads of 34–61 kg over 10- to 20-km distances) lead to postmarch decrements in marksmanship and grenade throw distance.^{53,84,112,165} The decrements in marksmanship are presumably attributable to small movements of the rifle resulting from fatigue of the upper body muscle groups, fatigue-induced tremors, or elevated heart rate or respiration.^{112,165,166} Marksmanship decrements last for only short periods of time.⁵³ The decrements in grenade throw distance may be due to a nerve entrapment syndrome^{157,161} or pain in the shoulder area, both resulting from the pressure of the rucksack straps. Lower body muscular power (as measured by the vertical jump and Wingate test) and muscle strength do not appear to be adversely affected by prolonged pack load carriage.^{84,112,165,167}

Conclusions: Improving Soldier Mobility

This review suggests many ways of facilitating soldier mobility including load reductions, load redistribution, equipment modifications, and physical training. Load reductions can be accomplished by tailoring the load to the specific operations and by using special load-handling devices. Commanders must make realistic risk analyses and take only the equipment necessary for the mission. Special combat load carts are available that could be useful in special situations such as marches on unobstructed terrain or in close resupply operations.^{19,76} Reducing loads will lower energy cost, increase soldier comfort, and may reduce some types of injuries, especially blisters, back problems, and metatarsalgia.

Equipment modifications should first focus on redistributing the load about the center of mass of the body. Many military carriage systems have vests and belts that have pockets and attachment points useful for moving some items from the rucksack to the front of the body. Items carried on the front of the body should be those likely to be needed quickly or needed often. Pack frames and well-padded hip belts provide several benefits including reduced loads on the shoulder, greater comfort for the shoulders, and a possible reduction of some types of injuries. Frames and hip belts may improve soldiers' performance on tasks requiring the use of the upper body. Load shifting through the use of belts and buckles (e.g., sternum straps to move loads to different points on the shoulder) may also be helpful. The optimal distribution of the center of mass of load within the rucksack may depend on the type of terrain. On roads or well-graded paths, placement of heavy items high in the pack is preferable to lower energy cost, maintain a more upright body posture, and possibly reduce lower back problems. On uneven terrain, a more even distribution of the load within the pack may be more helpful to maintain stability.

Regular physical training that includes aerobic exercise, resistance exercise, and road marching can improve load-carriage performance. Road marching should be conducted at least twice a month with loads that soldiers are expected to carry in unit

operations. Loads and distances should be increased gradually over sessions until a maintenance level has been achieved. New unit members should be given time to adapt through the same gradual program. Regular physical training has been shown to improve march performance and may reduce some types of injuries.

It is desirable to reduce load-carriage-related injuries that impair performance, cause discomfort and disability and result in a loss of manpower. Blister incidence can be reduced by keeping the feet dry, and this can be accomplished by (1) the use of an polyester inner socks combined with wool or wool-polypropylene outer socks, (2) antiperspirants applied at least 3 days before a march and reapplied at least once a week, and (3) frequent sock changes. The use of Spenco insoles and the distribution of loads more evenly around the torso can also reduce blister incidence. Aerobic physical training combined with regular load-carriage marches and cessation of tobacco use may reduce the incidence of stress fractures and blisters. The use of frames and hip belts can reduce the incidence of rucksack palsy.

Soldier mobility can be improved by lightening loads, improving equipment and load distribution, appropriate physical training, and specific techniques directed at injury prevention. Suitable changes will allow soldiers to complete missions at lower energy costs, with more comfort, with fewer injuries, and with a greater likelihood of mission accomplishment.

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