MILITARY MEDICINE, 169, 1:45, 2004

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

Guarantor: MAJ Joseph J. Knapik, USA (Ret.)
Contributors: MAJ Joseph J. Knapik, USA (Ret.)*; COL Katy L. Reynolds, USA (Ret.)†; Everett Harman, PhD†

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 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 Agency[19] 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.

*Directorate of Epidemiology and Disease Surveillance, U.S. Army Center for Health Promotion and Preventive Medicine, Aberdeen Proving Ground, MD 21010.

†U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760.

Presented at the North Atlantic Treaty Organization's Research and Technology Conference entitled "Soldier Mobility: Innovations in Load Carriage System Design and Evaluation," June 2000, Kingston Ontario, Canada.

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as official Department of the Army position, policy or decision, unless so designated by other official documentation. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of this organizations.

This manuscript was received for review in October 2001. The revised manuscript was accepted for publication in May 2003.

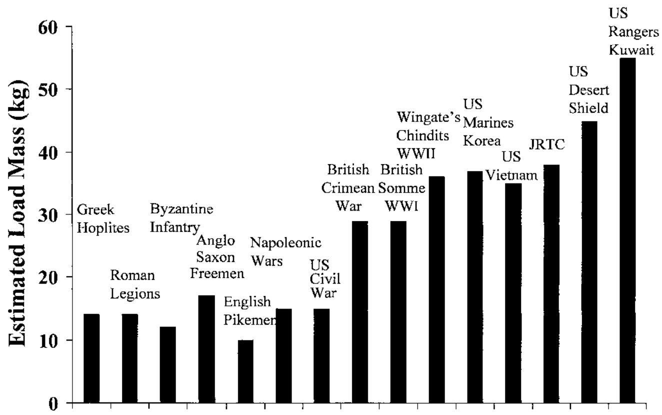

Fig. 1. Loads carried on the march by various infantry units throughout history.[7–11] JRTC, Joint Readiness Training Center (Fort Chaffee, Arkansas, unpublished data).

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]

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)[e]	177	79

NA, Not available.

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 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 impairments[36] 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

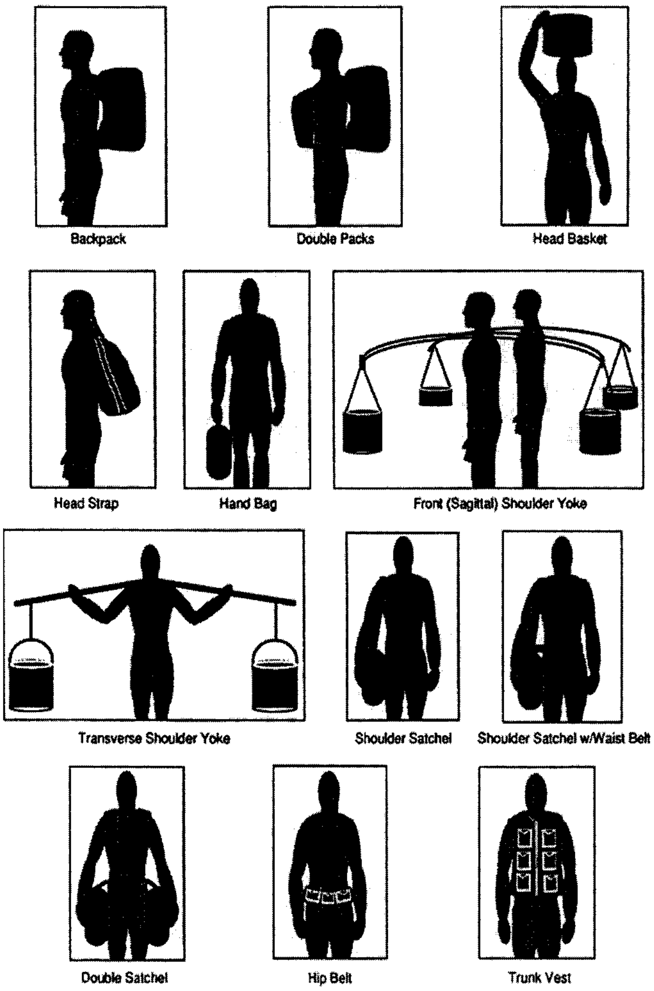

Fig. 2. Methods of load carriage.

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 saggital 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

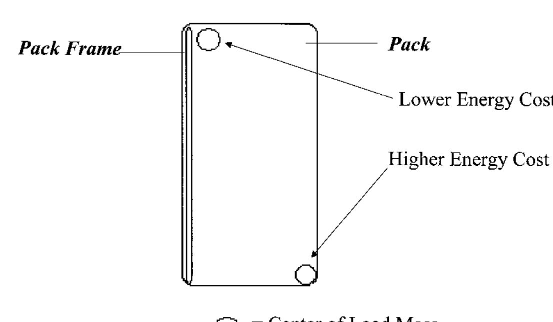

Fig. 3. Effect of placement of the load in the backpack on energy cost.[61]

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 VO_{2max} = 51 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) 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 kg[79] and the speed at which military women completed a 5-km distance carrying 19 kg[80] 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 breath (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 Goldman[94] 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] 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: $W_{td} = W_1 + (2.4\,(m_t \times g \times \mathrm{h} \times \mathrm{s}^{-1}) \times 0.3^{(\alpha/7.65)}$, 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/s^2), $h \times s^{-1}$ 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.

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.

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 MARCH[104]

Injury	During March[a] Continued March (*n*)	During March[a] Did Not Continue March (*n*)	1–12 Days Postmarch[b] (*n*)	Totals *N*	Totals %
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 MARCH[105]

Injury	During March[a] Continued March (*n*)	During March[a] Did Not Continue March (*n*)	1–15 Days Postmarch[b] (*n*)	Totals *N*	Totals %
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 backpack,[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 preparation 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 study[105] 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 inclination[131–134] 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. Sutton[136] 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 study[104] 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 anterioposteriorly 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 recruits[137–142] 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 calcaneous,[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.

Acknowledgments

We thank MAJ James Nagel, Mr. William Harper, and Dr. Rene dePontbriand for their helpful comments on this manuscript. Shelby Choate produced the figure on load-carrying methods.

References

1. Carre ET: Historical review of the load of the foot-soldier. Tentage and Equipage Series Report 8. Natick, MA, United States Army Quartermaster Research and Development Center, 1952.
2. Lothian NV: The load carried by the soldier. J R Army Med Corps 1921; 37: 38:241–263, 342–351, 448–458, 9–24.
3. Marshall SLA: The Soldier's Load and the Mobility of a Nation. Quantico, VA, Marine Corps Association, 1950.
4. Renbourn ET: The knapsack and pack. J R Army Med Corps 1954; 100:1–15, 77–88, 193–200.
5. Dubik JM, Fullerton TD: Soldier overloading in Grenada. Milit Rev 1987; 67: 38–47.
6. Marsh AR: A short but distance war: the Falklands campaign. J R Soc Med 1983; 76: 972–82.
7. Lothian NV: The load carried by the soldier. J R Army Med Corps 1922; 38: 9–24.
8. Downs F: The Killing Zone. New York, Berekey Publishing Co, 1978.
9. Holmes R: Acts of War: The Behavior of Men in Battle. New York, MacMillan and Co, 1985.
10. Porter SC: The soldier's load. Infantry 1992; May-June: 19–22.
11. Kragh JF, Taylor DC: Parachuting injuries: a medical analysis of an airborne operation. Milit Med 1996; 161: 67–9.
12. Lothian NV: The load carried by the soldier. J R Army Med Corps 1921; 37: 342–51.
13. Lothian NV: The load carried by the soldier. J R Army Med Corps 1921; 37: 241–63.
14. Lothian NV: The load carried by the soldier. J R Army Med Corps 1921; 37: 448–58.
15. Cathcart EP, Richardson DT, Campbell W: Army Hygiene Advisory Committee report 3 on the maximal load to be carried by the soldier. J R Army Med Corps 1923; 41: 12–24.
16. Bailey TL, McDermott WM: Review of research on load carrying. Tentage and Equipage Series Report 9, Natick, MA, United States Army Quartermaster Research and Development Center, 1952.
17. U.S. Army Combat Developments Agency: A study to reduce the load of the infantry combat solider. Fort Benning, GA, U. S. Army Combat Developments Command, 1962.
18. U.S. Army Combat Developments Agency: A study to conserve the energy of the combat infantryman. Fort Belvior, VA, U. S. Army Combat Developments Command, 1964.
19. U.S. Army Development and Employment Agency (ADEA): Report on the ADEA soldier's load initiative. Fort Lewis, WA, ADEA, 1987.
20. Kennedy SJ: Forward. In Review of Research on Load Carriage. Edited by Baily TL, McDermott WM. Natick, MA, U.S. Army Quartermaster Research and Development Center, 1952.
21. Sampson JB, Leitch DP, Kirk J, Raisanen GS: Front-End Analysis of Load Bearing Equipment for the U.S. Army and U. S. Marine Corps. Technical Report NATICK/TR-95/024. Natick, MA, U.S. Army Soldier Systems Command, 1995.
22. Sampson J: Technology Demonstration for Lighting the Soldier's Load. Technical Report TR-88/027L. Natick, MA, U.S. Army Natick Research and Development Laboratory, 1988.
23. Kennedy SJ: The Carrying of Loads within an Infantry Company. Technical Report 73–51-CE. Natick, MA, U.S. Army Natick Laboratories, 1963.
24. Knapik JJ, Staab J, Bahrke M, et al: Relationship of Soldier Load Carriage to Physiological Factors, Military Experience and Mood States. Technical Report T17-90. Natick, MA, United States Army Research Institute of Environmental Medicine, 1990.
25. Eaton SB, Konmer MJ: Stone age nutrition: implications for today. Contemp Nutr 1985; 10: 1–2.
26. Friedl KE: Body composition and military performance: origins of the Army standards. In Body Composition and Military Performance. Edited by Marriott BM, Grumstrup-Scott J. Washington, DC, National Academy Press, 1992.
27. Sharp MA, Patton JF, Knapik JJ, et al: A comparison of the physical fitness of men and women entering the U.S. Army during the years 1978–1998. Med Sci Sports Exerc 2002; 34: 356–63.
28. Vogel JA, Crowdy JP: Aerobic fitness and body fat of young British males entering the Army. Eur J Appl Physiol 1978; 40: 73–83.
29. Gooderson CY, Beebee M: Anthropometry of 500 infantrymen 1973–1974. Report 17/76. Farnsborough, England, Army Personnel Research Establishment, 1976.
30. Vogel JA, Patton JF, Mello RP, Daniels WL: An analysis of aerobic capacity in a large United States population. J Appl Physiol 1986; 60: 494–500.
31. Legg SJ: Comparison of different modes of load carriage. Ergonomics 1985; 28: 197–221.
32. Das SK, Saha H: Climbing efficiency with different modes of load carriage. Ind J Med Res 1966; 9: 866–71.
33. Datta SR, Ramanathan NL: A preliminary investigation of the ergonomics of load carrying. Indian J Physiol Allied Sci 1967; 21: 134–42.
34. Datta SR, Ramanathan NL: Ergonomic comparison of seven modes of carrying loads on the horizontal plane. Ergonomics 1971; 14: 269–78.
35. Balogun JA: Ergonomic comparison of three modes of load carriage. Int Arch Occup Environ Health 1986; 58: 35–46.
36. Legg SJ, Mahanty A: Comparison of five modes of carrying a load close to the trunk. Ergonomics 1985; 28: 1653–60.
37. Maloiy GMO, Heglund NC, Prager LM, Cavagna GA, Taylor CR: Energetic cost of carrying loads: have African women discovered an economic way? Nature 1986; 319: 668–9.
38. Kram R: Carrying loads with springy poles. J Appl Physiol 1991; 71: 1119–22.
39. Bloswick DS, Gerber A, Sebesta D, Johnson S, Mecham W: Effect of mailbag design on musculoskeletal fatigue and metabolic load. Hum Factors 1994; 36: 210–8.
40. Heglund HC, Willems PA, Penta M, Cavagna GA: Energy saving gait mechanics with head-supported loads. Nature 1995; 375: 52–4.
41. Winsmann FR, Goldman RF: Methods for evaluation of load-carriage systems. Percept Mot Skills 1976; 43: 1211–8.
42. Soule RG, Goldman RF: Energy cost of loads carried on the head, hands, or feet. J Appl Physiol 1969; 27: 687–90.
43. Malhotra MS, Gupta JS: Carrying of school bags by children. Ergonomics 1965; 8: 55–60.
44. Ramanathan NL, Datta SR, Gupta MN: Biomechanics of various modes of load transport on level ground. Ind J Med Res 1972; 60: 1702–10.
45. Lloyd R, Cooke CB: The oxygen consumption associated with unloaded walking and load carriage using two different backpack designs. Eur J Appl Physiol 2000; 81: 486–92.
46. Johnson RC, Pelot RP, Doan JB, Stevenson JM: The effect of load position on

biomechanical and physiological measures during a short duration march. Proceeding of the Soldier Mobility: Innovations in Load Carriage System Design and Evaluation. Kingston, Ontario, Canada, NATD Scientific and Technical Workshop, 2001.
47. Harman EA, Frykman PN, Knapik JJ, Han KH: Backpack vs. front-back: differential effects of load on walking posture. Med Sci Sports Exerc 1994; 26: S140.
48. Kinoshita H: Effects of different loads and carrying systems on selected biomechanical parameters describing walking gait. Ergonomics 1985; 28: 1347–62.
49. Lloyd R, Cooke CB: Kinetic changes associated with load carriage using two rucksack designs. Ergonomics 2000; 43: 1331–41.
50. Harman E, Frykman P, Pandorf C, et al: Physiological, biomechanical, and maximal performance comparisons of female soldiers carrying loads using prototype U.S. Marine Corps Modular Lightweight Load-Carrying Equipment (MOLLE) with Interceptor Body Armor and U.S. Army All-Purpose Lightweight Individual Carrying Equipment (ALICE) with PASGT Body Armor. Technical Report T9-99. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 1999.
51. Harman EA, Han KI, Frykman PN, Pandorf. CE: The effects of backpack weight on the biomechanics of load carriage. Technical Report T00–19. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 2000.
52. Johnson RF, Knapik JJ, Merullo DJ: Symptoms during load carriage: effects of mass and load distribution during a 20-km road march. Percept Mot Skills 1995; 81: 331–8.
53. Knapik JJ, Ang P, Meiselman H, Johnson W, Kirk J, Bensel C, Hanlon W: Soldier performance and strenuous road marching: influence of load mass and load distribution. Milit Med 1997; 162: 62–7.
54. Holewijn M: Physiological strain due to load carrying. Eur J Appl Physiol 1990; 61: 237–45.
55. Vacheron JJ, Poumarat G, Chandezon R, Vanneuville G: The effects of loads carried on the shoulders. Milit Med 1999; 164: 597–9.
56. Kirk J, Schneider DA: Physiological and perceptual responses to load carrying in female subjects using internal and external frame backpacks. Technical Report NATICK/TR-91/023. Natick, MA, U.S. Army Natick Research, Development and Engineering Center, 1991.
57. Harman EA, Obusek JP, Frykman PN, Palmer CJ, Bills RK, Kirk. J: Backpacking energy-cost and physical performance: internal vs. external frame, belt vs. no-belt. Med Sci Sports Exerc 1997; 29: S205.
58. Jacobson B, Jones K: Comparison of selected perceptual variables for backpacks with internal and external frames. Percept Mot Skills 2000; 90: 605–8.
59. Holewijn M, Lotens WA: The influence of backpack design on physical performance. Ergonomics 1992; 35: 149–57.
60. Legg SJ, Perko L, Campbell P: Subjective perceptual methods for comparing backpacks. Ergonomics 1997; 40: 809–17.
61. Obusek JP, Harman EA, Frykman PN, Palmer CJ, Bills RK: The relationship of backpack center of mass to the metabolic cost of load carriage. Med Sci Sports Exerc 1997; 29: S205.
62. Bloom D, Woodhull-McNeal AP: Postural adjustments while standing with two types of loaded backpacks. Ergonomics 1987; 30: 1425–30.
63. Hellebrandt FA, Fries EC, Larsen EM, Kelso LEA: The influence of the Army pack on postural stability and stance mechanics. Am J Physiol 1944; 140: 645–55.
64. Bobet J, Norman RW: Effects of load placement on back muscle activity in load carriage. Eur J Appl Physiol 1984; 53: 71–5.
65. Knapik JJ, Harman E, Reynolds K: Load carriage using packs: a review of physiological, biomechanical and medical aspects. Appl Ergon 1996; 27: 207–16.
66. Legg SJ, Mahanty A: Energy cost of backpacking in heavy boots. Ergonomics 1986; 29: 433–8.
67. Catlin MJ, Dressendorfer RH: Effect of shoe weight on the energy cost of running. Med Sci Sports 1979; 11: 80.
68. Jones BH, Toner MM, Daniels WL, Knapik JJ: The energy cost and heart-rate response of the trained and untrained subjects walking and running in shoes and boots. Ergonomics 1984; 27: 895–902.
69. Martin PE: Mechanical and physiological responses to lower extremity loading during running. Med Sci Sports Exerc 1985; 17: 427–33.
70. Vanderbie JH: Some experimental load distributions studied on the treadmill. Climatic Research Laboratory Report 212. Natick, MA, U.S. Army Quartermaster Research and Development Division, Environmental Protection Branch, 1953.
71. Knapik JJ, Harper W, Crowell HP, Leiter K, Mull B: Standard and alternative methods of stretcher carriage: performance, human factors, and cardiovascular responses. Ergonomics 2000; 43: 639–52.
72. Lind AR, McNicol GW: Cardiovascular responses to holding and carrying weights by hands and by shoulder harness. J Appl Physiol 1968; 25: 261–7.
73. Vanderlaan JC, Turlington RC, Tarter DN: Combat load cart (MANCART). Report ADEA-AR-88-A214. Fort Lewis, WA, Army Development and Employment Agency, 1988.
74. Haisman MF, Winsmann FR, Goldman RF: Energy cost of pushing loaded handcarts. J Appl Physiol 1972; 33: 181–3.
75. Haisman MF, Goldman RF: Effect of terrain on the energy cost of walking with back loads and handcart loads. J Appl Physiol 1974; 36: 545–8.
76. Harman EA, Frykman PN: Heavy load carriage performance correlates: backpack vs. individual towed trailer. Med Sci Sports Exerc 1995; 27: S136.
77. Taylor CR, Heglund NC, McMahon TA, Looney TR: Energetic cost of generating muscular force during running: a comparison of large and small animals. J Exp Biol 1980; 86: 9–18.
78. Rudzki SJ: Weight-load marching as a method of conditioning Australian Army Recruits. Milit Med 1989; 154: 201–5.
79. Kraemer WJ, Vogel JA, Patton JF, Dziados JE, Reynolds KL: The effects of various physical training programs on short duration, high intensity load bearing performance and the Army Physical Fitness Test. Technical Report T30-87. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 1987.
80. Knapik JJ, Gerber J: Influence of physical fitness training on the manual material handling capability and road marching performance of female soldiers. Technical Report ARL-TR-1064. Aberdeen Proving Ground, MD, Human Research and Engineering Directorate, U. S. Army Research Laboratory, 1996.
81. Knapik J, Bahrke M, Staab J, Reynolds K, Vogel J, O'Connor J: Frequency of loaded road march training and performance on a loaded road march. Technical Report T13-90. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 1990.
82. Harman EA, Frykman PN, Lammi ER, Palmer CJ: Effects of a physically demanding training program on women's heavy work task performance. Med Sci Sports Exerc 1996; 28: S128.
83. Martin PE, Nelson RC: The effect of carried loads on the walking patterns of men and women. Ergonomics 1986; 29: 1191–202.
84. Harper W, Knapik JJ, Pontbriand RD: An investigation of female load carriage capability. Technical Report ARL-TR-1176. Aberdeen Proving Ground, MD, U.S. Army Research Laboratory, 1997.
85. Harper WH, Knapik JJ, Pontbriand RD: Equipment compatibility and performance of men and women during heavy load carriage. Proc Hum Factors Ergon Soc 1997; 2: 604–8.
86. Bobbert AC: Energy expenditure in level and grade walking. J Appl Physiol 1960; 15: 1015–21.
87. Borghols EAM: Influence of heavy weight carrying on the cardiorespiratory system during exercise. Eur J Appl Physiol 1978; 38: 161–9.
88. Goldman RF, Iampietro PF: Energy cost of load carriage. J Appl Physiol 1962; 17: 675–6.
89. Soule RG, Pandolf KB, Goldman RF: Energy expenditure of heavy load carriage. Ergonomics 1978; 21: 373–81.
90. Polcyn AF, Bensel CK, Harman EA, Obusek JP: The effect of load weights: a summary of maximal performance, physiological and biomechanical results from four studies of load-carriage systems. Kingston, Ontario, Canada, Proceeding of the Soldier Mobility, Innovations in Load Carriage System Design and Evaluation, 2001.
91. Pandolf KB, Haisman MF, Goldman RF: Metabolic energy expenditure and terrain coefficients for walking on snow. Ergonomics 1976; 19: 683–90.
92. Soule RG, Goldman RF: Terrain coefficients for energy cost prediction. J Appl Physiol 1972; 32: 706–8.
93. Pandolf KB, Givoni B, Goldman RF: Predicting energy expenditure with loads while standing or walking very slowly. J Appl Physiol 1977; 43: 577–81.
94. Givoni B, Goldman RF: Predicting metabolic energy cost. J Appl Physiol 1971; 30: 429–33.
95. Duggan A, Haisman MF: Prediction of the metabolic cost of walking with and without loads. Ergonomics 1992; 35: 417–26.
96. Pimental NA, Pandolf KB: Energy expenditure while standing or walking slowly uphill or downhill with loads. Ergonomics 1979; 22: 963–73.
97. Pimental NA, Shapiro Y, Pandolf KB: Comparison of uphill and downhill walking and concentric and eccentric cycling. Ergonomics 1982; 25: 373–80.
98. Wanta DM, Nagle FJ, Webb P: Metabolic response to graded downhill walking. Med Sci Sports Exerc 1993; 25: 159–62.
99. Margaria R: Positive and negative work performances and their efficiencies in human locomotion. Int Z Angew Physiol 1968; 25: 339–51.
100. Santee WR, Allison WF, Blanchard LA, Small MG: A proposed model for load carriage on sloped terrain. Aviat Space Environ Med 2001; 72: 562–6.
101. Epstein Y, Rosenblum J, Burstein R, Sawka MN: External load can alter the energy cost of prolonged exercise. Eur J Appl Physiol 1988; 57: 243–7.
102. Patton JF, Kaszuba J, Mello RP, Reynolds KL: Physiological responses to pro-

longed treadmill walking with external loads. Eur J Appl Physiol 1991; 63: 89–93.
103. Sagiv M, Ben-Sira D, Sagiv A, Werber G, Rotstein A: Left ventricular responses during prolonged treadmill walking with heavy load carriage. Med Sci Sports Exerc 1994; 26: 285–8.
104. Knapik J, Reynolds K, Staab J, Vogel JA, Jones B: Injuries associated with strenuous road marching. Milit Med 1992; 157: 64–7.
105. Reynolds KL, White JS, Knapik JJ, Witt CE, Amoroso PJ: Injuries and risk factors in a 100-mile (161-km) infantry road march. Prev Med 1999; 28: 167–73.
106. Myles WS, Eclache JP, Beaury J: Self-pacing during sustained, repetitive exercise. Aviat Space Environ Med 1979; 50: 921–4.
107. Cooper DS: Research into foot lesions among Canadian field forces, Proceeding of the 13th Commonwealth Defence Conference on Operational Clothing and Combat Equipment. Malaysia, CDA-11, 1981.
108. Knapik JJ, Reynolds KL, Duplantis KL, Jones BH: Friction blisters: pathophysiology, prevention and treatment. Sports Med 1995; 20: 136–47.
109. Akers WA, Sulzberger MB: The friction blister. Milit Med 1972; 137: 1–7.
110. Hoeffler DF: Friction blisters and cellulitis in a Navy recruit population. Milit Med 1975; 140: 333–7.
111. Reynolds KL, Kaszuba J, Mello RP, Patton JF: Prolonged treadmill load carriage: acute injuries and changes in foot anthropometry. Technical Report T1/91. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 1990.
112. Knapik J, Johnson R, Ang P, et al: Road march performance of special operations soldiers carrying various loads and load distributions. Technical Report T14-93. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 1993.
113. Knapik JJ, Reynolds KL, Barson J: Influence of antiperspirants on foot blisters following road marching. Technical Report ARL-TR-1333. Aberdeen Proving Ground, MD, U.S. Army Research Laboratory, 1997.
114. Knapik JJ, Reynolds K, Barson J: Risk factors for foot blisters during road marching: tobacco use, ethnicity, foot type, previous illness and other factors. Milit Med 1999; 164: 92–7.
115. Spence WR, Shields MN: Insole to reduce shear forces on the sole of the feet. Arch Phys Med Rehabil 1968; 49: 476–9.
116. Spence WR, Shields MN: New insole for prevention of athletic blisters. J Sports Med 1968; 8: 177–80.
117. Smith W, Walter J, Bailey M: Effects of insoles in Coast Guard basic training footwear. J Am Podiatr Med Assoc 1985; 75: 644–7.
118. Naylor PFD: The skin surface and friction. Br J Dermatol 1955; 67: 239–48.
119. Herring KM, Richie DH: Friction blisters and sock fiber composition. J Am Podiatr Med Assoc 1990; 80: 63–71.
120. Euler RD: Creating “comfort” socks for the U. S. consumer. Knitting Times 1985; 54: 47–50.
121. Allan JR, Macmillan AL: The Immediate Effects of Heat on Unacclimatized Paratroops. Exercise “Tiger Brew II.” Research Memorandum 16/62. Farnbourgh, U.K., U.K. Army Operational Research Establishment, 1963.
122. Whittingham DGV: A Further Investigation of Some of the Effects of Marching in Flying Boots: Exercise Orthopod II. Flying Personnel Research Committee Report 751. Farnborough, U.K., R.A.F. Institute of Aviation Medicine, 1951.
123. Knapik JJ, Hamlet MP, Thompson KJ, Jones BH: Influence of boot sock systems on frequency and severity of foot blisters. Milit Med 1996; 161: 594–8.
124. Darrigrand A, Reynolds K, Jackson R, Hamlet M, Roberts D: Efficacy of antiperspirants on feet. Milit Med 1992; 157: 256–9.
125. Juhlin L, Hansson H: Topical glutaraldehyde for plantar hyperhidrosis. Arch Dermatol 1968; 97: 327–30.
126. Knapik JJ, Reynolds K, Barson J: Influence of an antiperspirant on foot blister incidence during cross country hiking. J Am Acad Dermatol 1998; 39: 202–6.
127. Brandrup F, Larsen PO: Axillary hyperhidrosis: local treatment with aluminium chloride hexahydrate 25% in absolute ethanol. Acta Dermatoven 1978; 58: 461–5.
128. Reynolds KL, Darrigrand A, Roberts D, Knapik J, Pollard JA, Jones BH, Duplantis KL: Effects of an antiperspirant with emollients on foot sweat accumulation and blister formation while walking in the heat. J Am Acad Dermatol 1995; 33: 626–30.
129. Jones BH, Reynolds KL, Rock PB, Moore MP: Exercise related musculoskeletal injuries: risks, prevention and care. In ACSM’s Resource Manual for Guidelines for Exercise Testing and Prescription. Edited by Durstine JL, King AC, Painter PL, Roman JL, Zwiren LD. Philadelphia, PA, Lea and Febiger, 1993.
130. Dalen A, Nilsson J, Thorstensson A: Factors Influencing a Prolonged Foot March. FOA Report C50601-H6. Stockholm, Sweden, Karolinska Institute, 1978.
131. Hale CJ, Coleman FR, Karpovich PV: Trunk Inclination in Carrying Low and High Packs of Various Weights. Natick, MA, U.S. Army Quartermaster Research and Development Division, Environmental Protection Division, 1953.
132. Harman E, Han KH, Frykman P, Johnson M, Russell F, Rosenstein M: The effects on gait timing, kinetics, and muscle activity of various loads carried on the back. Med Sci Sports Exerc 1992; 24: S129.
133. Norman RW: The Utility of Combining EMG and Mechanical Work Rate Data in Load Carriage Studies. Boston, MA, Proceedings of the 4th Congress of the International Society of Electrophysiological Kinesiology, 1979.
134. Pandorf CE, Harman EA, Frykman PN, Obusek JP, Smith TJ: A comparison of the load carriage biomechanics of male and female soldiers. Med Sci Sports Exerc 1999; 31: S190.
135. Pierrynowski MR, Norman RW, Winter DA: Metabolic measures to ascertain the optimal load to be carried by man. Ergonomics 1981; 24: 393–9.
136. Sutton EL: Preparing for combat: athletic injuries incurred and performance limiting orthopedic and medical conditions. Med Sci Sports Exerc 1976; 8: 74.
137. Brudvig TGS, Gudger TD, Obermeyer L: Stress fractures in 295 trainees: a one-year study of incidence as related to age, sex, and race. Milit Med 1983; 148: 666–7.
138. Elton RC, Abbott HG: An unusual case of multiple stress fractures. Milit Med 1965; 130: 1207–10.
139. Giladi M, Milgrom C, Danon Y, Aharonson Z: The correlation between cumulative march training and stress fractures in soldiers. Milit Med 1985; 150: 600–1.
140. Gilbert RS, Johnson HA: Stress fractures in military recruits: a review of 12 years’ experience. Milit Med 1966; 131: 716–21.
141. Jones BH: Overuse injuries of the lower extremities associated with marching, jogging and running: a review. Milit Med 1983; 148: 783–7.
142. Jones BH, Harris JM, Vinh TN, Rubin C: Exercise-induced stress fractures and stress reactions of bone: epidemiology, etiology and classification. In Exercise Sports Science Review. Edited by Pandolf KB. Baltimore, MD, William and Wilkins, 1989.
143. Donald JG, Fitts WT: March fractures: a study with special reference to etiological factors. J Bone Joint Surg 1947; 29: 297–300.
144. Garcia JE: Factors associated with stress fractures in military recruits. Milit Med 1987; 152: 45–8.
145. Wilson ES, Katz FN: Stress fractures. Radiology 1969; 92: 481–6.
146. Darby RE: Stress fractures of the os calcis. JAMA 1967; 247: 1039–41.
147. Hullinger CW, Tyler WL: March fracture: report of 313 cases. Bull US Army Med Depart 1944; 69:72–80.
148. Hannson CJ: On insufficiency fractures of the femur and tibia. Acta Radiol 1938; 19: 554.
149. Hamilton SA, Finklestein HE: March fracture: a report of a case involving both fibulae. J Bone Joint Surg 1944; 26: 146–7.
150. Winfield AC, Moore J, Bracker M, Johnson CW: Risk factors associated with stress reactions in female Marines. Milit Med 1997; 162: 698–702.
151. Lappe JM, Stegman MR, Recker RR: The impact of lifestyle factors on stress fractures in female Army recruits. Osteoporos Int 2001; 12: 35–42.
152. Gardner LI, Dziados JE, Jones BH, et al: Prevention of lower extremity stress fractures: a controlled trial of a shock absorbent insole. Am J Public Health 1988; 78: 1563–7.
153. Friedl KE, Nuovo JA, Patience TH, Dettori JR: Factors associated with stress fractures in Army women: indications for further research. Milit Med 1992; 157: 334–8.
154. Beck TJ, Ruff CB, Mourtada FA, et al: Dual energy X-ray absorptiometry derived structural geometry for stress fracture prediction in male U.S. Marine Corps recruits. J Bone Miner Res 1996; 11: 645–53.
155. Ozburn MS, Nichols JW: Pubic ramus and adductor insertion stress fractures in female basic trainees. Milit Med 1981; 146: 332–4.
156. Walsh MW: Knee injuries. In The Team Physician Handbook. Edited by Mellon MB, Walsh WM, Sheldon GL. Boston, MA, Mosby-Year Book, 1990.
157. Bessen RJ, Belcher VW, Franklin RJ: Rucksack paralysis with and without rucksack frames. Milit Med 1987; 152: 372–5.
158. Daube JR: Rucksack paralysis. JAMA 1969; 208: 2447–52.
159. Hauser CU, Martin WF: Two additional cases of traumatic winged scapula occurring in the Armed Forces. JAMA 1943; 121: 667–8.
160. Ilfeld FW, Holder HG: Winged scapula: case occurring in soldier from knapsack. JAMA 1942; 120: 448–9.
161. Wilson WJ: Brachial plexus palsy in basic trainees. Milit Med 1987; 152: 519–22.
162. Martin PE, Nelson RC: The effect of carried loads on the combative movement performance of men and women. Milit Med 1985; 150: 357–62.
163. Harman EA, Frykman PN, Pandorf CE, Obusek JP, Smith TJ: A comparison of male and female soldier performance of physically demanding simulated combat tasks. Med Sci Sports Exerc 1999; 31: S394.

164. Harman EA, Pandorf CE, Frykman PN, Obusek JP: Maximal speeds of locomotion and obstacle course traversal as functions of carried loads. Med Sci Sports Exerc 2001; 33: S99.
165. Knapik JJ, Staab J, Bahrke M, Reynolds K, Vogel J, O'Conner J: Soldier performance and mood states following strenuous road marching. Milit Med 1991; 156: 197–200.
166. Tharion WJ, Moore RJ: Effects of carbohydrate intake and load bearing exercise on rifle marksmanship performance. Technical Report T9-93. U.S. Army Research Institute of Environmental Medicine, 1993.
167. Patton JF, Kaszuba J, Mello RP, Reynolds KL: Physiological and perceptual responses to prolonged treadmill load carriage. Technical Report T11-90. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 1989.