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REPORT NO. T19-89

# LOADS CARRIED BY SOLDIERS: HISTORICAL, PHYSIOLOGICAL, BIOMECHANICAL AND MEDICAL ASPECTS

U S ARMY RESEARCH INSTITUTE  
OF  
ENVIRONMENTAL MEDICINE  
Natick, Massachusetts

JUNE 1989



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1a. REPORT SECURITY CLASSIFICATION <b>Unclassified</b>		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE			
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION US Army Research Institute of Environmental Medicine		6b. OFFICE SYMBOL (if applicable) SGRD-UE-PH	7a. NAME OF MONITORING ORGANIZATION Same as 6a.
6c. ADDRESS (City, State, and ZIP Code)		7b. ADDRESS (City, State, and ZIP Code)	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO. 62787A	PROJECT NO. BE162787A87
		TASK NO. BF	WORK UNIT ACCESSION NO. DA315433
11. TITLE (Include Security Classification) Loads carried by soldiers: Historical Physiological, Biomechanical and Medical Aspects			
12. PERSONAL AUTHOR(S) Joseph Knapik, CPT, MS			
13a. TYPE OF REPORT Technical Report	13b. TIME COVERED FROM <u>Oct 88</u> to <u>May 89</u>	14. DATE OF REPORT (Year, Month, Day) .June 1989	15. PAGE COUNT 50
16. SUPPLEMENTARY NOTATION			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
			Road marching, loads, weight, energy expenditure, injuries, muscle strength, biomechanics, VO <sub>2</sub> max, load carriage
19. ABSTRACT (Continue on reverse if necessary and identify by block number)			
<p>Throughout history foot soldiers have experienced cycles where they were required to carry heavy loads followed by periods where loads were reduced. Since the 18th century total loads have progressively increased far beyond those carried in previous times. This may be due to technical developments that have increased soldier firepower and protection at the expense of the heavier load. The height and weight of British and American soldiers appears to have increased since the Industrial Revolution possibly allowing heavier load carriage. Loads currently recommended by the U.S. Army Infantry school are 33 kg for an approach march load (45% of body weight) and 22 kg for a combat load (30% of body weight). Methods of reducing loads include the use of lightweight technology, load tailoring, auxiliary transport systems, doctrinal changes, and physical training.</p> <p>Specific physiological factors involved in load carriage include aerobic capacity and muscle strength. The specific muscle groups involved in load carriage have been examined using correlational approaches, EMG analysis and strength changes after marching. These studies</p>			
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION	
22a. NAME OF RESPONSIBLE INDIVIDUAL		22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

A.

## 19. Abstract (continued)

suggest that most of the functional muscle groups of the lower body (hip extensors, knee flexors and extensors, ankle plantar flexors), are involved in load carriage performance. It also appears that the trunk extensors may be important. The muscle groups of the upper body have not been adequately explored. A combination of jogging, interval training and resistance training will improve load carriage performance over short distances. Marching with loads in combination with other military training appears to increase  $\dot{V}O_2$  max in recruits,

The energy cost of load carriage is minimized if the load is placed as close to the center of mass of the body as possible. Energy cost increases progressively with an increase in the speed of marching, the load or the grade. March velocity decreases in a linear manner with load. When marching at a steady velocity with a load less than 40% body weight, energy cost is steady over time; however, at high loads (greater than 60% body weight) energy cost increases progressively over time.

Self pacing results in a lower energy cost than a forced pace. Soldiers self pace for short periods (1-3.5 h) at about 45%  $\dot{V}O_2$  max. For long periods (2-6 days) soldiers self pace at about 32%  $\dot{V}O_2$  max. This emphasizes the importance of aerobic capacity since soldiers with a higher  $\dot{V}O_2$  max can march at a faster pace.

Loads carried on the feet increase the energy cost of 0.7 to 1.0% for every additional 0.1 kg. The double pack has a lower energy cost than the backpack, allows a more normal gait and is preferred by subjects. However, military requirements favor the backpack: it allows more freedom of movement and can be quickly shed.

Lower extremity injuries are those most commonly experienced in load carriage. These include blisters, tendonitis, and stress fractures. Rucksack paralysis is most often seen in recruits but can occur in experienced soldiers. Incidence of rucksack paralysis can be reduced by use of a framed pack with a hipbelt.

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HUMAN RESEARCH

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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TECHNICAL REPORT

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LOADS CARRIED BY SOLDIERS:  
A REVIEW OF HISTORICAL, PHYSIOLOGICAL,  
BIOMECHANICAL AND MEDICAL ASPECTS

by

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June 1989

## ACKNOWLEDGEMENTS

I would like to thank Dr. Everett Harman, MAJ Katy Reynolds, CPT Heidi Heckle, LTC Bruce Jones, Dr. John Patton and Dr. James Vogel for their helpful comments on specific parts of this manuscript.

## FOREWORD

This paper is a literature review performed as part of a research protocol examining physical training programs to improve load carriage performance (USARIEM Protocol No. PH-1-89). Previous reviews on load carriage (5, 51, 89) have been limited in scope and/or have not included topics of interest from the standpoint of physical fitness and physical training. This paper specifically addresses these and other issues.



## TABLE OF CONTENTS

	<u>Page</u>
Acknowledgements	i
Foreword	ii
Table of Contents	iii
List of Figures	iv
List of Tables	v
Abstract	vi
Introduction	1
Historical Aspects	2
Loads Carried Through the Ages	2
Nineteenth and Twentieth Century Efforts to Reduce Loads	6
European Efforts	6
American Efforts	6
Historical Perspective on Current U.S. Efforts	9
Load Tailoring	9
Load Carriage Systems	9
Physical Training	10
Height and Weight as Factors in Load Carriage	10
Physiological Aspects	13
Physiological Correlates of Load Carriage	13
Physical Training for Load Carriage	14
Load Carriage and $\dot{V}O_2$ max	14
Traditional Physical Training and Load Carriage	14
Local Muscle Fatigue and Discomfort	15
Energy Cost of Load Carriage	16
General Findings	16
Self Pacing	17
Economy of Movement	20
Loads on the Hands and Feet	21
Methods of Load Carriage	22
Biomechanical Aspects	23
Electromyographic Studies	23
Mechanical Studies	24
Medical Aspects	24
Rucksack Paralysis	24
Stress Fractures	25
Other Injuries	28
References	28
Appendix 1	38
Distribution List	39

## LIST OF FIGURES

	<u>Page</u>
1. Loads Carried By Various Armies	3
2. Predictive Equations For Estimating The Energy Cost Of Walking And Running With Backpack Loads	18
3. Energy Cost of Load Carriage	19

## LIST OF TABLES

	<u>Page</u>
1. Loads Carried by Various Units and/or Carried at Various Times	4
2. Current and Projected Loads (Including Clothing and Personal Equipment) for 9 U.S. Army Light Infantry Positions (kg)	5
3. SLA Marshall's Recommendation for the Soldier's Combat Load	11
4. Heights and Weights of Soldiers and General Populations	12

## ABSTRACT

Throughout history foot soldiers have experienced cycles where they were required to carry heavy loads followed by periods where loads were reduced. Since the 18th century total loads have progressively increased far beyond those carried in previous times. This may be due to technical developments that have increased soldier firepower and protection at the expense of the heavier load. The height and weight of British and American soldiers appears to have increased since the Industrial Revolution possibly allowing heavier load carriage. Loads currently recommended by the U.S. Army infantry school are 33 kg for an approach march load (45% of body weight) and 22 kg for a combat load (30% of body weight). Methods of reducing loads include the use of lightweight technology, load tailoring, auxiliary transport systems, doctrinal changes, and physical training.

Specific physiological factors that appear to be involved in load carriage include aerobic capacity and muscle strength. The specific muscle groups involved in load carriage have been examined using correlational approaches, EMG analysis and strength changes after marching. These studies suggest that most of the functional muscle groups of the lower body (hip extensors, knee flexors and extensors, ankle plantar flexors), are involved in load carriage performance. It also appears that the trunk extensors may be important. The muscle groups of the upper body have not been adequately explored. A combination of jogging, interval training and resistance training will improve load carriage performance over short distances. Marching with loads in combination with other military training appears to increase  $\dot{V}O_2$ max in recruits.

The energy cost of load carriage is minimized if the load is placed as close to the center of mass of the body as possible. March velocity decreases in a

linear manner with load. Energy cost increases progressively with an increase in the velocity of marching, the load or the grade. Energy cost increases over time if the load or velocity is high enough (40% body weight at 5 km/h or 60% body weight at 4 km/h).

Self pacing results in a lower energy cost than a forced pace. Soldiers self pace for short periods (1-3.5 h) at about 45%  $\dot{V}O_{2max}$ . For long periods (2-6 days) soldiers self pace at about 32%  $\dot{V}O_{2max}$ . This emphasizes the importance of aerobic capacity since soldiers with a higher  $\dot{V}O_{2max}$  can march at a faster pace.

Loads carried on the feet increase the energy cost by 0.7 to 1.0% for every additional 0.1 kg. The double pack has a lower energy cost than the backpack, allows a more normal gait and is preferred by subjects. However, military requirements favor the backpack: it allows more freedom of movement and can be quickly shed.

Lower extremity injuries are those most commonly experienced in load carriage. These include blisters, tendonitis, and stress fractures. Rucksack paralysis is most often seen in recruits but can occur in experienced soldiers. Incidence of rucksack paralysis can be reduced by use of a framed pack with a hipbelt.

## INTRODUCTION

The single occupational task that best characterizes the U.S. Army light infantry soldier is that of load carriage. Light divisions have limited transportation assets so the soldier must, in many cases, depend on his personal mobility to move his equipment to the battle. Due to technical advances the individual soldier has a wide array of equipment he can use to increase his firepower and protection (79). However, the commander is faced with deciding which equipment to take on a particular mission. In attempting to prepare for the multiple threats of the battlefield the commander often overloads the individual soldier.

The carrying of loads by troops is an important aspect of military operations that can become critical in some situations. Overloading of soldiers with ammunition and equipment can lead to excessive fatigue and impair the soldier's ability to fight. Military historians (14, 68, 69, 87) point out numerous examples where heavy loads directly or indirectly resulted in unnecessary deaths and lost battles. The recent experience of the British in the Falklands and the U.S. Army in Grenada suggests overloading of soldiers is an even more serious problem today (29, 71).

The purpose of this paper is to review the literature on historical, physiological, biomechanical and medical aspects of load carriage. The historical review is limited to secondary sources. Other reviews have been completed by Haisman (51), Robertson (89) and Bailey and McDermott (5).

## HISTORICAL ASPECTS

### LOADS CARRIED THROUGH THE AGES

Lothian (68) examined available sources to determine loads carried by the soldiers of various armies up to WWI. These are summarized in Figure 1. The variations in the loads reflect at least 2 overlapping processes: 1) the conflict between the tendency to equip the soldier for a wide variety of threats on the battlefield and the requirements for tactical mobility and 2) technological and/or tactical changes that have altered the nature of warfare. For example, heavily armored cavalry displaced infantry altogether in the middle ages. The development of arrows that could penetrate this heavy armor led to a resurgence of light infantry. The introduction of firearms was countered by the development of protective shields that weighed as much as 23 kg. However, as firearms developed more penetrating power these shields disappeared (68).

Note in Figure 1 the discrepancy between the weight carried by the soldier and the equipment he actually owned. Up to the 18th century soldiers carried loads that seldom exceeded 15 kg. His extra equipment was moved by auxiliary transport including assistants, camp followers, horses, and carts. After the 18th century this auxiliary transport was deemphasized and more disciplined armies assured that troops carried their own loads. During the Crimean War (1854-1856) British and French infantry loads were estimated to be about 29 and 33 kg, respectively. British loads were reduced to 25 kg in 1907 but increased to 32-36 kg in WWI (68, 69).

Loading of the soldier did not stop after WWI. Holmes (52) and Kennedy et al. (58) cite the loads shown in Table 1 for a variety of operations from WWI to the Falklands Campaign. Recently, the U.S. Army Employment and Development Agency (ADEA) studied 9 light infantry positions in a "worst case"

FIGURE 1.  
LOADS CARRIED BY VARIOUS ARMIES  
OR AT VARIOUS TIMES  
(FROM LOTHIAN (58))

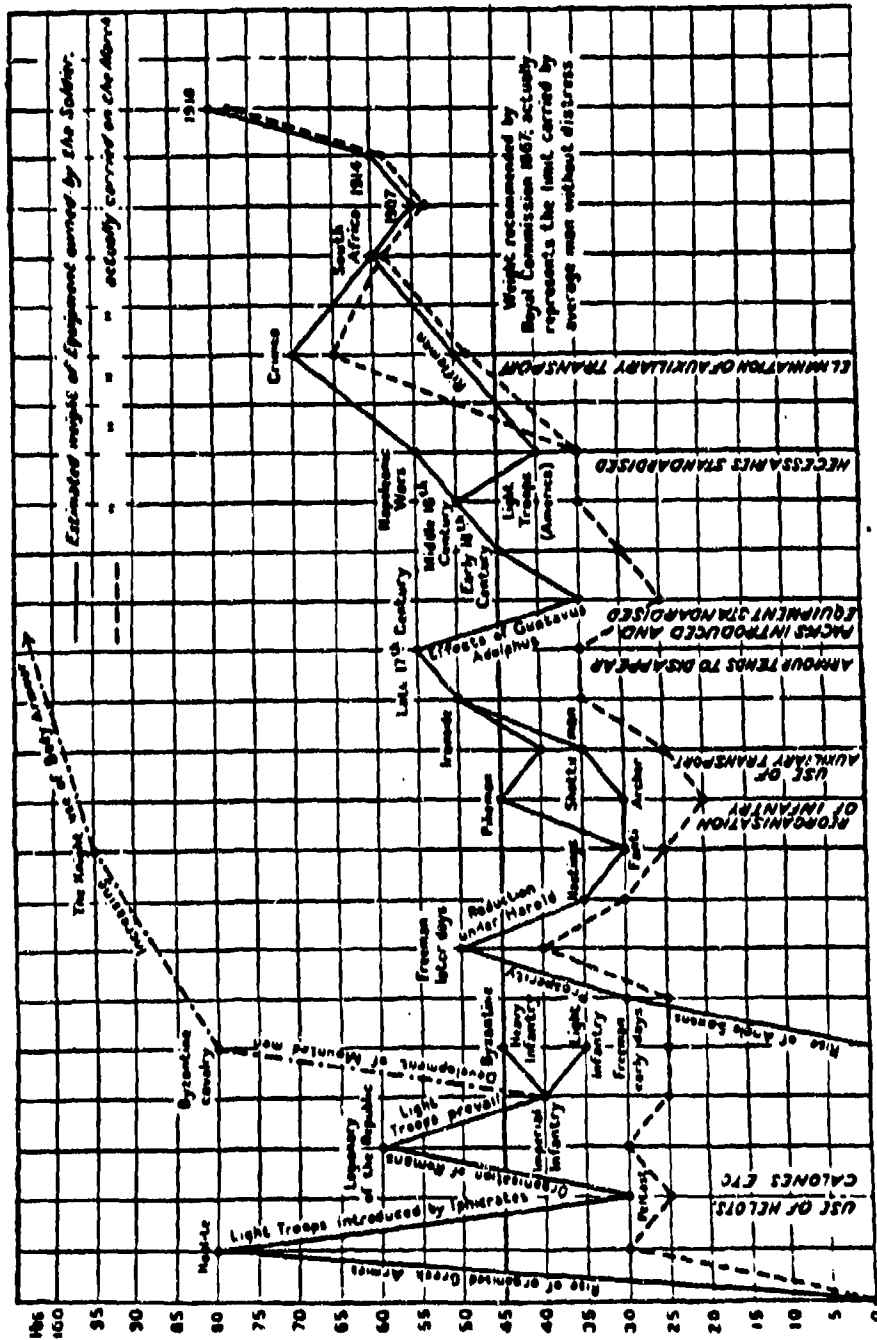




TABLE 1  
 Loads Carried by Various Units  
 and/or Carried at Various Times\*

<u>UNIT</u>	<u>Weight(kg)</u>
French Poilu (WWI)	39
British Infantry on the Somme (WWI)	30
French Foreign Legion (WWI)	45
Wingate's Chindits (WWII)	32-41
U.S. Forces in North Africa (WWII)	60
U.S. Marines in Korea	38
U.S. in Vietnam**	34
Falklands Campaign	54

\*From Holmes (52)

\*\*32 kg pack noted by Downs (28)

TABLE 2  
 Current and Projected Loads (Including Clothing  
 and Personal Equipment) for 9 U.S. Army  
 Light Infantry Positions (kg)\*

<u>Position</u>	<u>Current Weight</u>	<u>Expected Weight Due to New Technologies</u>
Assistant Dragon Gunner	76	74
Assistant Machine Gunner	69	59
Radio Telephone Operator	68	64
Dragon Gunner	64	61
Rifleman	62	64
Saw Gunner	59	57
Platoon Leader	58	54
Machine Gunner	58	53
Grenadier	56	53

\* From ADEA (3)

scenario. The loads carried by soldiers in these positions are shown in Table 2 and range from 56 to 76 kg (3).

## NINETIETH AND TWENTIETH CENTURY EFFORTS TO REDUCE LOADS

### European Efforts

After the Crimean War, a British "Committee Appointed to Inquire into the Effects of the Present System of Carrying Accoutrements, Ammunition and Kit of the Infantry Soldier" recommended that soldier loads be reduced to 21 kg through the elimination of "necessaries", especially underclothing (68, 87). Studies at the Fredrick William Institute in 1895 showed that soldiers could "tolerate" marching 24 km with a 22 kg load if the weather was cool. In warm weather this test caused "minor disturbances" from which the men recovered in 1 day (68). In 1908 a British "Committee on the Physiological Effects of Food, Training and Clothing of the Soldier" developed an improved web gear that was used in WWI (87). With the development of indirect calorimetry Cathcart et al. (15) were able to study the energy cost of 2 men marching at a variety of paces and loads. They found that the energy cost per unit weight was lowest when subjects carried a load equal to 40% of body weight. Energy cost rose as the load decreased or increased beyond this weight. The Hygiene Advisory Commission of the British Army in the 1920's recommended that the soldier's load should not exceed 18 to 20 kg or 1/3 body weight on the march (69).

### American Efforts

There is little information on American efforts to formally reduce soldier loads prior to WWII. Under the direction of the Quartermaster General, CPT H. W. Taylor developed a soldier's "Pay Load Plan". This was an attempt to unburden the soldier by providing him only the items needed for combat. There were also

various attempts to develop segmented packs: if the tactical situation required, a portion of the pack containing combat non-essential items could be left behind (59).

From 1948-1950 the U.S. Army Field Board No. 3 (Ft. Benning, GA) performed a number of studies on load carriage. They noted that previous work had ignored the individual soldier's load with respect to their position within the tactical organization. They found that loads ranged from 25 kg (rifleman) to 50 kg (ammunition carrier). In cooperation with the Surgeon General's Office, the Board expanded the study to determine how these loads should be reduced to make the soldier more combat effective. Metabolic data and the limits placed on the soldier in combat were considered. Based on a review of the literature, the board determined that the energy available for marching (basal metabolic rate subtracted out) could not exceed 3680 kcals/day. They recommended that the rifleman carry only 18 kg under the worst conditions; 25 kg was recommended as the maximum weight on the march (5).

SLA Marshall (63) came to a similar conclusion. He studied the report of the British board of 1920 and tempered this with actual combat experience. He recommended soldiers carry no more than 18 kg in combat. His recommended equipment list is shown in Table 3.

The U.S. Army Infantry Combat Developments Agency (98, 99) reinforced the weight recommendations of the Army Field Board No. 3. They recommended a load of 18 kg or 30% body weight for a conditioned fighting soldier and 25 kg or 45% body weight for a soldier on the march. They developed the concept of a "fighting load" and an "existence load".

More recently ADEA (2) and the U.S. Army Infantry School (107) have called the load carried by the soldier the "combat load". This is the mission

essential equipment required by soldiers to fight, survive, and complete their combat mission. The combat load is divided into a "fighting load" and an "approach march load". The fighting load is carried when enemy contact is expected or stealth is necessary. It consists of the soldier's clothing, load bearing equipment (LBE), helmet, weapon, rations, bayonet, and ammunition. The approach march load is carried in more prolonged operations. It includes the combat load plus a pack, sleeping roll, extra clothing, rations and extra ammunition. ADEA recommended 22 kg for the fighting load and 33 kg for the approach march load. This is in line with the U.S. Army Infantry School recommendations of 30% body weight as an optimal load and 45% body weight as a maximal load (13) since the average weight of the infantry soldier is 73 kg (101). These recommendations have been reinforced in other infantry publications (72, 82) and are taught at the U.S. Army Infantry School.

ADEA (3) proposed 5 approaches to lighten the U.S. Army infantry soldier's load. The first approach is the development of lighter weight components; however, current technological developments are expected to reduce the load by only 6% overall (91, see Table 1). The second approach is the soldier load planning model. This is a computer program that aids commanders in tailoring the soldier's loads through a risk analysis based on the METT-T (mission, enemy, terrain, time, troops). The third approach involves the development of specialized load handling equipment. This includes such things as hand carts and all terrain vehicles. The fourth approach is a reevaluation of current doctrine. An example of this is an increased emphasis on marksmanship to reduce ammunition loads. The fifth and final approach is the development of special physical training programs to condition soldiers to better tolerate load carriage.

## HISTORICAL PERSPECTIVE ON CURRENT U.S. EFFORTS

Many of the approaches proposed by ADEA are not new. Historical examples of three of these approaches are described below.

### Load Tailoring

Load tailoring has been practiced by commanders throughout history. Iphicrates of ancient Greece developed a light infantry armed with only a wooden shield, lance and sword. They defeated a Spartan force of heavily equipped hoplites. In the Seventeenth Century Adolphus of Sweden lightened his soldiers by removing armor and shortening weapons. The British Army in the Boer War carried only arms, ammunition, water and a haversack for a total weight of 11 kg (68).

Soldiers in battle have often reduced their loads on their own initiative. The confederate troops of Stonewall Jackson carried only rifles, ammunition, some food, and a blanket or rubber sheet. They discarded extra clothing, overcoats and knapsacks (68, 69). Marshall (69) cites the example of American paratroopers that jumped into Normandy in 1944. They exited the aircraft with a full load (about 36 kg) but once on the ground they quickly discarded equipment they considered unnecessary.

### Load Carriage Systems

Load carriage systems have also been used throughout history. Greek hoplites used helots to carry their equipment on the march. Carts and pack animals were probably used by the Roman Legions. Cromwell's Armies used "pack boys". Napoleon used carts whenever possible to relieve his soldiers of their marching loads. Camp followers also carried much of the soldiers load during various wars (14, 68).

### Physical Training

Lothian (68) provides several examples of how physical training has been used to improve marching with loads. Roman legionnaires are estimated to have performed road march training 3 times a month. They probably marched 32 km at a rate of about 5 km/h carrying a 20 kg pack. Cromwell and the Duke of Wellington emphasized marching with loads. In Cromwell's Army (1640) pay was contingent on marching 24 km on a regular basis. The French Chasseurs (WWI) marched two times a week over 13 to 18 km carrying a "light kit". Germans (WWI) took recruits out on an initial 10 km march; 1 km was added weekly until a 20 km march could be completed in "full kit".

McMichael (73) gives a brief description of the training of Wingate's Chindits who fought as light infantry in the Burma Campaign in WWII. "[They were] loaded with huge 34 kg packs and marched unmercifully through man-killing terrain". They performed a 225 km road march just prior to their deploying to Burma.

Knapik and Drews (62) report that units within the U.S. Army 10th Mountain Division routinely road march with their fighting loads about 3 times a month. Training guidance prescribes a quarterly road march of 40 km (11 minutes/km pace); yearly they march 161 km in 5 days.

### HEIGHT AND WEIGHT AS FACTORS IN LOAD CARRIAGE

The height and weight of the soldier has been recognized as important factors in load carriage (58). The larger soldier may be able to carry a heavier load by virtue of greater bone and muscle mass.

It has been estimated that humans have increased their height about 10 cm since the industrial revolution (31). Table 4 provides a summary of the heights

**TABLE 3**  
**SLA Marshall's (69) Recommendation for**  
**the Soldier's Combat Load**

<u>ITEM</u>	<u>WEIGHT(kg)</u>
<b>Uniform</b>	
Underwear	0.3
Fatigues	1.4
Cap	0.1
Boots	2.0
Belt	0.1
<b>Equipment</b>	
Ammunition Belt (2/48 rds, M1)	1.1
Canteen (full, with cover)	1.3
First Aid Pack	0.2
Helmet (with liner)	1.4
Rifle (M1 with bayonet)	4.9
Grenades (2)	1.4
Light Pack (with 1 K-ration, mess kit, and personal items)	3.9
	-----
TOTAL	18.0



**TABLE 4**  
**Heights and Weights of Soldiers**  
**and General Populations**

	<u>Ht(cm)</u>	<u>Wt(kg)</u>	<u>Avg/Min*</u>
<b>HISTORICAL INFORMATION (68)</b>			
<b>Soldiers</b>			
Roman Legionnaire Recruits	170		Min
French (Napoleonic Era, 1776)	165		Min
French (Napoleonic Era, 1792)	163		Min
French (Napoleonic Era, 1813)	152		Min
French (Crimean War)	163	56	Avg
British (Post WWI)	168	59	Avg
French (Post WWI)	163		Avg
<b>General Populations (1902-1911)</b>			
Austrian	155		Avg
Belgian	157		Avg
German	157		Avg
Italian	157		Avg
Swedish	160		Avg
Spanish	155		Avg
U.S.	160		Avg
<b>RECENT SAMPLES</b>			
<b>British</b>			
Recruits (102)	175	70	Avg
Infantry (43)	175	73	Avg
<b>U.S.</b>			
Recruits (101)	175	68	Avg
Infantry (101)	173	73	Avg

\*Avg/Min - Average or Minimum

and weights of various groups derived from a variety of sources. Prior to the Crimean War only minimum standards are available. U.S. and British Army recruits and infantry soldiers are taller and heavier than those of the Crimean War and WWI period.

## PHYSIOLOGICAL ASPECTS

### PHYSIOLOGICAL CORRELATES OF LOAD CARRIAGE

Two investigations have correlated a variety of physiological measures with load carriage tasks. Dziados et al. (30) had 49 soldiers complete a 16 km course as rapidly as possible with a 18 kg load. Time on this task was significantly related to  $\dot{V}O_2$ max and 3 measures of knee flexion strength. Mello et al. (74) tested 28 soldiers carrying a 46 kg load. Soldiers completed distances of 2, 4, 8 and 12 km as rapidly as possible. At the 2 shorter distances there were no significant correlations with any physiological measure. At the 2 longer distances various measures of knee flexion and knee extension strength were significantly correlated with time to complete the distances.  $\dot{V}O_2$ max was also significantly correlated with time to complete the 12 km distance. Neither of these 2 studies investigated anaerobic capacity or upper body strength.

A study by Bassey et al. (7) suggests plantar flexor strength is related to walking speed. These investigators measured isometric plantar flexion strength of 56 males who were over 65 years of age. Walking speed was measured as subjects walked at a normal pace on an outdoor course; an accelerometer was used to measure the total number of steps over a 7 day period. Both walking speed and total steps were significantly correlated with plantar flexion strength (R=0.42 and 0.30)

## PHYSICAL TRAINING FOR LOAD CARRIAGE

### Load Carriage and $\dot{V}O_2\text{max}$

Two studies have demonstrated that  $\dot{V}O_2\text{max}$  can be improved by physical training with loads. Shoenfeldt et al. (93) showed that individuals with low initial fitness levels (about 30 ml/kg•min) could significantly improve their predicted  $\dot{V}O_2\text{max}$  with loaded marching. Subjects marched 5 km/h, 30 min/day, 5 days/wk carrying rucksack loads of only 3 to 6 kg. However, more fit subjects (about 45 ml/kg•min) did not improve.

On the other hand carrying heavier loads combined with other military training does seem to improve aerobic capacity of fit soldiers. Rudzki (90) studied 2 platoons of Australian recruits. One platoon followed the normal training of the Australian Army which prescribed running, especially in the early part of training. Another platoon replaced all running with load carriage marches (and carried their rucksacks with them to all lessons). The latter group increased their loads progressively from 16 to 29 kg. The initial predicted  $\dot{V}O_2\text{max}$ s were 54 and 51 ml/kg•min for the run and march groups, respectively. At the end of the 11 week training cycle the run group increased their  $\dot{V}O_2\text{max}$  by 12% and the march group by 9%. Five km run times did not differ between the groups at the end of training.

### Traditional Physical Training and Load Carriage

Kreamer et al. (63) examined the influence of a 12 week training program on the time required by soldiers to complete a 3.2 km course with a 45 kg load. They found that alone, neither resistance training nor high intensity endurance training (HIET, jogging and interval training) improved load carriage times. However, an upper and lower body resistance program combined with HIET

improve load carriage performance 15%; a program with upper body resistance training and HIET resulted in an 11% improvement.

Problems with this study include the short distance for the load carriage task and the high training frequency. The 3.2 km course allowed subjects to run the entire distance. Running may involve different fitness components than the long distance marches the light infantry typically performs. The training program involved 4 days per week of strength training (10-22 muscle groups), 2 days per week of interval training and 2 days per week of distance running. The daily duration of training was 2 to 2.5 h. Typically, most units in the U.S. Army allow only 1 h per day for physical training.

#### LOCAL MUSCLE FATIGUE AND DISCOMFORT

Some authors (46, 64) have suggested that the limiting factor in load carriage is fatigue of local muscle groups. Clarke et al. (17) specifically tested this hypothesis by examining strength decrements after a series of loaded marches. Subjects carried 13-28 kg packs over a 4.8 km course at a rate of 4.8 km/h. Subjects used packs with and without hip belts. The investigators used cable tensiometers to measure the isometric strength of 10 muscle groups before and after the marches. These included the hand grip, ankle plantar flexors, pectorals, knee flexion and extension, hip flexion and extension, trunk flexion and extension, and shoulder elevation. The muscle groups showing the greatest overall strength losses were the trunk extensors, hip extensors, knee flexors and ankle plantar flexors. When using the pack with the hip belt, the trunk extensors, hip extensors and knee flexors showed the greatest strength losses.

Three studies examined subjective reports of discomfort and soreness after loaded road marching. Dalen et al. (20) interviewed Swedish conscripts after a 20-26 km road march on which they carried a 15 kg pack. Problems with the

legs and feet were most commonly reported as limiting factors for the march (42%); general fatigue was reported in some cases (11%). Gupta (46) reported that local fatigue of the back and shoulders was more important than the energy cost in limiting load carriage. Legg and Mahanty (65) found that subjective reports of discomfort varied depending on the mode of load carriage. For rucksacks with and without frames as well as double packs the majority of discomfort was in the neck and shoulder region. For a backpack with a hip belt discomfort was localized to the mid trunk and upper legs. For a jacket type load discomfort was reported in the shoulders and upper trunk.

### ENERGY COST OF LOAD CARRIAGE

#### General Findings

Numerous investigations have been performed on the energy cost of load carriage. Some general findings are as follows. In order to minimize energy expenditure, the load should be located as close as possible to the center of mass of the body (18, 95, 104). Energy cost per unit weight is the same whether the weight is that of the body or a backpack (11, 42, 94). Factors that influence energy cost include terrain (50, 95), velocity and grade (11, 42, 60, 96). Walking velocity decreases in a linear manner with load (53, 76). There is no difference in cost for loads carried high verses low on the back (22).

Givoni and Goldman (41) used some of the above relationships to develop an equation (Figure 2a) for predicting energy cost of loaded walking. Pandolf et al. (81) revised this equation (Figure 2b) and included a factor for the energy cost of standing. Figure 3 shows the increase in energy cost as the load is increased using the Pandolf et al. (81) equation. While Norman et al. (80) showed this same curvilinear relationship, Gordon et al. (44) and Gupta (46) show the relationship to be more linear.

Pimental and Pandolf (83) and Pimental et al. (84) tested the formula in Figure 2b using slopes of 0-10% and loads of 0-40 kg. For slow walking (2.2 km/h) the formula predicted high but at faster velocities (4 km/h) the formula was accurate. Pierrynowski et al. (85) found the equation resulted in lower values than those actually obtained for loads of 0-34 kg at 5 km/h. Cymerman et al. (19) verified that the equation was accurate for energy expenditures up to 628 kcal/h at an altitude of 4300 m.

Epstein et al. (32) developed a predictive equation for determining energy cost of running with and without backpack loads (Figure 2c). This formula incorporates the equation of Pandolf et al. (81) as one of its variables. Epstein et al. (33) later noted that walking with heavy loads ( $\geq 40$  kg) resulted in an increase in energy cost over time. Since the predictive equations in Figure 1 assume a steady state they will not be accurate when carrying heavy loads for long periods of time.

#### Self Pacing

Zarrugh and Radcliff(106) showed that self pacing resulted in a lower energy cost than a forced pace. Hughes and Goldman (53) estimated that men performing self paced loaded walking have an energy expenditure of 425 kcal/h $\pm$ 10%. Evans et al. (34) confirmed this but showed that the relative exercise intensity of 45%  $\dot{V}O_2$ max was a slightly better predictor for walks of 1-2 h with loads up to 20 kg. However, Levine et al. (67) found that trained subjects self paced at 35%  $\dot{V}O_2$ max (447 kcal/h) and untrained subjects at 44%  $\dot{V}O_2$ max (434 kcal/h) for a 2.5-3.5 h walk. The untrained subjects had approximately the same  $\dot{V}O_2$ max as those of Evans et al. (34). It was therefore

## FIGURE 2

### Predictive Equation for Estimating The Energy Cost of Walking and Running with Backpack Loads

Figure 2a. Givoni and Goldman (41). Energy Cost of Loaded Walking

$$M_w = N (W+L) (2.3 + 0.32(V-2.5)^{1.65} + G (0.2+0.07(V-2.5)))$$

Figure 2b. Pandolf et al. (81). Energy Cost of Standing and Walking Slowly  
With and Without Loads

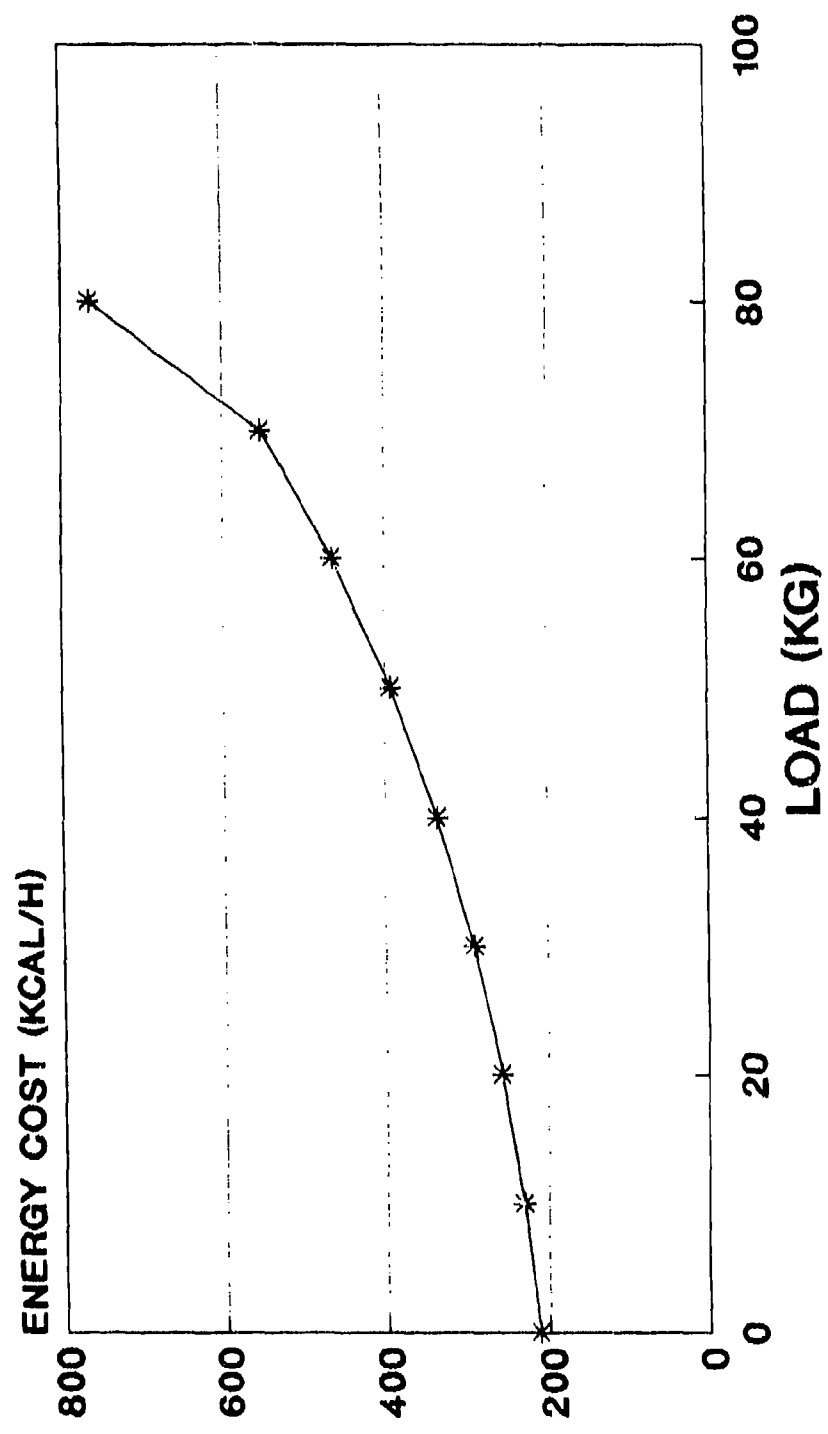
$$M_w = 1.5W + 2(W+L) (L/W)^2 + N(W+L)(1.5V^2 + 0.35VG)$$

Figure 2c. Epstein et al. (33). Energy Cost of Running With and Without  
Backpack Loads

$$M_r = M_w - 0.5(1-0.01L) (M_w - 15L - 850)$$

Symbols:  $M_w$  = Metabolic Cost of Walking (Watts)  
 $M_r$  = Metabolic Cost of Running (Watts)  
 $W$  = Subject Weight (kg)  
 $L$  = Load Carried (kg)  
 $N$  = Terrain Factor  
 $V$  = Walking Velocity (m/sec)  
 $G$  = Slope or Grade (%)

**FIGURE 3. ENERGY COST OF LOAD CARRIAGE**  
(EQUATION OF PANDOLF ET AL., 1977)



(73 KG MAN, 4.2 KM/H, LEVEL ROAD)



suggested that trained subjects may not have been able to reach higher energy expenditures because they were only allowed to walk. This hypothesis is supported by estimates from the study of Dziadosz et al. (30). Subjects were allowed to run and used an average of 521 kcal/h or 43%  $\dot{V}O_{2max}$  for the 16 km course. The  $\dot{V}O_{2max}$  of these subjects was about the same as the trained subjects of Levine et al. (67).

Studies cited above have been limited to relatively short durations. Myles et al. (77) studied soldiers with a high aerobic capacity ( $\dot{V}O_{2max}=58.8$  ml/kg $\cdot$ min) during a 6 day road march covering 204 km. They walked about 6 h per day, self pacing and carrying packs averaging 23 kg. Soldiers marched at an estimated 37%  $\dot{V}O_{2max}$  (447 kcal/h) on the first day and then declined to an average 32%  $\dot{V}O_{2max}$  (384 kcal/h) on subsequent days.

These studies emphasize the importance of aerobic capacity for load carriage. Soldiers with a higher aerobic capacity will have a higher absolute energy output; they will complete the march more rapidly. If the march can be completed at a slower pace these soldiers will have a lower relative energy cost and will presumably fatigue less rapidly. They may also have more energy for critical tasks after the march.

#### Economy of Movement

An economic body movement is one that has a low energy cost. While this concept is easily understood, various authors have defined this somewhat differently by using different units of measure. Cathcart et al. (15) showed that energy cost (per unit total weight and distance) was lowest when soldiers carried loads equivalent to 40% of their body weight. Hughes and Goldman (47) showed a slightly lower energy cost (per unit total weight and distance) when men self paced and carried loads of 30-40 kg (44-59% body weight) compared to loads

heavier or lighter (0-60 kg range). Gordon et al. (44) found a decrease in energy cost (per unit weight) when men carried loads equivalent to 40% body weight when compared to loads higher or lower than this. It should be noted that these decreases in energy cost are small (3 to 6%). Energy cost progressively rises as the load increases (see Figure 3; 44, 46, 80, 81) and small gains in economy are of little practical consequence.

The studies cited above have looked only at short time periods. Epstein et al. (33) compared the energy cost of carrying a backback load of 25 kg (37% body weight) vs. a 40 kg load (59% body weight) for 2 h. Subjects walked at 4.5 km/h up a 5% grade. They found that energy cost over time remained the same for the 25 kg load; however, with the 40 kg load the energy cost rose in a linear manner with time (about 25 kcal/h). Patton et al. (81a) showed that this increase in energy cost over time was also dependent on the velocity of movement. They studied energy cost while soldiers carried loads of 40 and 63% of body weight at velocities of 4, 4.9 and 5.8 km/h on a level treadmill. Even at 40% body weight energy cost rose over time at 4.9 and 5.8 km/h. At 63% body weight energy cost rose over time at all 3 velocities.

Pierrynowski et al. (85) argued that the most efficient load depended on whether or not the individual's body weight was considered part of his load. If body weight was not considered, 40 kg was estimated to be the most efficient load. If body weight was considered 7 kg resulted in the greatest efficiency.

#### Loads on the Hands and Feet

Energy cost of running and walking increases as weights are added to the ankles or hands (4, 25, 56, 57, 75, 95, 105). The energy cost of ankle carriage exceeds that of hand carriage by 5 to 6 times if the hand weights are carried

close to the body (95); however, when vigorous arm movements are involved the energy cost of hand carriage can exceed that of ankle carriage (75).

Adding loads to the foot in the form of dead weight or as an increase in the weight of the footwear results in the same relative change in energy expenditure: for each 0.1 kg added to the foot the increase in energy expenditure is 0.7 to 1.0% (16, 56, 57, 66, 75). This emphasizes that footwear should be as light as possible consistent with durability requirements.

#### Methods of Load Carriage

Studies have been conducted to compare the energy cost of loads carried on the head, hands, back, low back, thighs, waist, and across one shoulder. These studies have generally concluded that the backpack has an energy cost equal to or lower than most other methods (22, 24, 26, 86, 100). However, the double pack, carried on the front and back of the body, has generally been shown to have a lower energy cost than the backpack alone (25, 86, 100). Legg and Mahanty (65) showed no difference between the double pack and backpack although they did show a trend for a lower energy in the case of the double pack. Subjects prefer the double pack (65) and have a more normal walking gait when carrying it (81).

The double pack appears to have some physiological and biomechanical advantages over the rucksack. However, military requirements favor the rucksack. The double pack can inhibit movement and limit the field of vision in front of the body. This may restrict tasks like firing weapons and putting on protective masks. Climbing and skiing may also be difficult. This type of pack may also be difficult to put on and take off, depending on the design.

The new U.S. Army load carriage system is called the Integrated Individual Fighting System (IIFS). Two components are the load bearing vest (replacing the LBE web gear) and the field pack (rucksack). The vest has front pockets to

carry 6, 30 magazines of M-16 ammunition and 2 fragmentation grenades. The total weight of this ammunition in the vest is 3.4 kg and this serves as a small load in front of the body. The field pack has an internal frame consisting of aluminum staves. The staves and suspension system are adjustable allowing the user to customize the pack to his body frame and preferences. The cover to the field pack is removable and serves as a "daypack" that is independent of the larger pack (78).

## BIOMECHANICAL ASPECTS

### ELECTROMYOGRAPHIC STUDIES

Frameless backpacks using loads 10-50% of body weight increased the electromyographic (EMG) activity of the vastus lateralis but not the semimembranosus/semitendinosus (38). Walking with loads of 7-20 kg reduced the EMG activity of the erector spinae when compared to unloaded walking (9, 18). This was presumably due to the backpack load which created a back extensor moment which offset the flexor moment of the head, arms, and trunk (9, 36). Trapezius EMG activity was lower if the backpack load was placed low on the back when compared to loads placed high on the back (9).

Norman et al. (80) showed the utility of combining EMG and cinematographic data in the study of load carriage. They showed that EMG activity of the trapezius, rectus femoris, gastrocnemus and erector spinae generally increased with an increase in the load. When subjects carried a 20 kg load there was an increase in mechanical work, no change in energy cost and thus an increase in efficiency (efficiency=work/energy cost). However, analysis of the cinematographic and EMG data revealed that the increase in mechanical work was

due to an undesirable resonance between the pack and the carrier. It has been suggested that futures studies using this approach could evaluate a wide variety of factors involved in load carriage (48).

### MECHANICAL STUDIES

The period of time that both feet are on the ground is unaffected by loads up to 50% body weight (38, 61, 70). The duration of the swing of the unsupported leg as it moves forward increased progressively as the load increased (38, 70). Subjects tended to lean forward (trunk angle increases) as the load increased (47, 61, 70). Vertical force components were higher with heavier loads as were maximal breaking and propelling forces (47).

Intraabdominal pressure (IAP) reduced the load placed on the spine in proportion to the amount of this pressure (6). During walking IAP rose and fell in a phasic manner due to activation and relaxation of the abdominal muscles. Backpack loads of 18 to 27 kg did not change the magnitude of this pressure while walking (45).

## MEDICAL ASPECTS

### RUCKSACK PARALYSIS

Various authors (8, 49, 54, 97, 103) have reported on a total of 33 cases of "rucksack paralysis" associated with load bearing marches. Clinical symptoms included minor pain, paresthesias, numbness and paralysis of the upper extremities. The shoulder girdle and elbow flexor muscle groups were usually most affected. "Winged scapula" was common in many cases. Symptoms were probably due to compression of the upper trunk of the brachial plexus. In some

cases symptoms and signs were compatible with C5 to C6 root lesions. Reports of discomfort in the neck and shoulder region associated with load carriage (46, 65) may be related to brachial plexus compression.

Bessen et al., (8) found that the incidence of rucksack paralysis was 7.4 times higher when soldiers used the current U.S. Army rucksack without a frame compared to using this pack with a frame and hip belt. When this injury did occur in soldiers using frames the only affected muscles appeared to be the serratus anterior suggesting thoracic nerve palsy. This study suggests that load distribution and use of the hip belt (reducing the load on the shoulders) may help prevent this problem.

### STRESS FRACTURES

Stress fractures have been associated with loaded road marching especially in recruits undergoing initial military training (12, 37, 53a). Nonmodifiable risk factors for this injury appear to be gender, age and race. The incidence of stress fractures in U.S. Army basic training is 1-2% for males and 10-20% for females (55). Older subjects are injured more often than younger ones (12, 37). Whites are injured more often than blacks, hispanics and other races (12, 37). Modifiable risk factors appear to be a previously sedentary lifestyle (37, 40) and possibly excess body weight (40). Injuries appear to increase as the kilometers of marching increase (53a, 55) although there is some contradictory information (39).

Shock absorbant boot insoles (viscoelastic polymers) did not reduce the number of stress fractures in recruits (37). However, elimination of running and jumping in the third week of U.S. Army basic training has been reported to reduce the incidence rate (92).

## OTHER INJURIES

Sutton (97) reported on injuries during a strenuous 7 month physical training program for a newly activated U.S. Army airborne ranger battalion. Weekly road marches of 16 to 32 km were performed. Road marching produced 9 cases of brachial plexus palsy and 141 cases of metatarsalgia.

Reynolds (88) and Flynn et al. (Appendix 1) reported on injuries occurring on 161 km load bearing tactical road marches performed by U.S. Army light infantry units. Soldiers carried estimated loads between 18 to 45 kg. The most common injuries were to the lower extremities. Flynn et al. noted that blisters, musculoskeletal injuries (stress fractures, anterior knee pain) and heat related problems accounted for 44%, 13% and 2%, respectively, of the medical complaints. Poor physical training, improper march technique, travel over gravel/stone surfaces, and inadequate load distribution may have contributed to these injuries.

Myles et al. (77) reported on a 204 km road march performed by 25 highly fit French infantry soldiers. They carried an average 23 kg backpack during the 6 day march. Foot disorders, especially blisters were the most common injuries. Myles et al. (77) also cite a 67 km march completed by British troops in the tropical heat of Singapore. Foot disorders accounted for 40% of the casualties whereas heat related conditions accounted for 32%.

Kinoshita (61) found that when a heavier load was carried (26 vs 13 kg) the foot rotated in an anterior-posterior plane around the distal end of the metatarsals for a longer period of time. He hypothesized that this may expose the metatarsals to mechanical stress for a longer period. This may explain the prevalence of metatarsalgia in Sutton's (97) study. Kinoshita (61) recommended that when carrying heavy weight, stride length should be reduced and flexible

boots used. This would more quickly transfer the body weight and help maintain normal joint function.

Dalen et al. (20) interviewed Swedish conscripts after they completed a 20-26 km road march carrying 15 kg. 85% of the soldiers reported foot problems and one half attributed these problems to their boots. Specific injuries and symptoms included blisters, transverse arch pain, tenderness over the medial tibia, pain in the back of the knee joint, and back pain.



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## APPENDIX 1

### AN ANALYSIS OF INJURIES INCURRED DURING A 100 MILE ROAD MARCH

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The effect of dermatological, orthopedic, and heat-related injuries on performance during a 100 mile road march was studied. 363 physically conditioned Light Infantry soldiers, each carrying a 25 pound combat pack, started the event. The march was conducted at a rate of approximately 20 miles per day for 5 consecutive days. The average temperature during marching hours was 75 degrees F and the terrain was varied. 149 soldiers (41%) completed the entire distance. Drop-out rate was 4% at 30 miles, with approximately the same number dropping out at 10 mile intervals. The average drop-out rate was 9% 5% at each 10 mile interval. The primary cause of non-completion was blisters to the plantar surface of the feet which accounted for a 44% drop-out rate. The next leading cause was orthopedic injuries (tendonitis, stress fractures, anterior knee pain) which resulted in a 13% morbidity. Heat-related injuries were responsible for 2% of the non-completions. The authors conclude that in an exercise of this magnitude, relatively minor dermatological and orthopedic conditions precluded 59% of those starting the road march from completing it. They also suggest a variety of preventative measures to be used during similar events to decrease morbidity.

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