TITLE: The Effects of Load Weight: A Summary Analysis of Maximal Performance, Physiological, and Biomechanical Results from Four Studies of Load-Carriage Systems

TITLE: Soldier Mobility: Innovations in Load Carriage System Design and Evaluation [la Mobilite du combattant: innovations dans la conception et l'evaluation des gilets d'intervention]

The Effects of Load Weight: A Summary Analysis of Maximal Performance, Physiological, and Biomechanical Results from Four Studies of Load-Carriage Systems

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Summary

Data from studies of standard and prototype load-carriage equipment were analyzed to determine the effects of the weight borne by male and female load carriers on time to traverse a 3.2-km course at self-paced, maximal speed and on energy expenditure and kinetic and kinematic variables during externally paced walking at 4.8 $km \cdot h^{-1}$. The equipment configurations included fighting, approach, and sustainment loads, with masses varying from 12 kg to 50 kg. It was found that course completion times and energy expenditure were directly related to the weight carried. The effects of load weight on the kinematic and kinetic variables were more complex. They included evidence of adaptations in walking gait that are likely to aid the load carrier in maintaining stability and in absorbing the increased forces associated with increased load on the body.

Introduction

For purposes of planning and executing military ground operations, the items worn and carried by U.S. soldiers are divided into three configurations (Department of the Army, 1990). The fighting load configuration is the lightest in weight. It consists of mission-related equipment that is essential for immediate and short-term combat maneuvers. This configuration includes the clothing being worn, a helmet, a weapon, ammunition, water, a belt and a vest with pockets for carrying some of the equipment, and, possibly, an armor vest. A second configuration, the approach march load configuration, is intended for use during prolonged, dynamic operations, such as marching to an assault point. The approach load consists of the components of the fighting load plus other items typically carried in a backpack, such as rations, a poncho, and additional ammunition and water. The third configuration, the heaviest, is the sustainment load configuration. This configuration includes the components of the approach load plus other items, such as a sleeping bag, a change of clothes, and additional ammunition, water, and rations.

The guidelines provided to military commanders indicate that weights of the fighting and the approach load configurations should not exceed 22 kg and 33 kg, respectively. However, the components of the load configurations, and thus the weights carried by ground troops, are not prescribed by military policy. Rather, field commanders are responsible for determining the components of troops' loads after assessing mission requirements and related situational factors (Department of the Army, 1990). The multiple threats on the battlefield and the dependence of mission success on adequate supplies can result in commanders overloading their soldiers. Troops often undertake prolonged marches while carrying heavy loads and still must be capable of engaging in strenuous activities once the objective is reached.

Studies of the effects of load carrying on soldiers' performance have focused mainly on the energy cost of carrying the load (Goldman & Iampietro, 1962; Pierrynowski, Winter, & Norman, 1981; Soule, Pandolf, &

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Goldman, 1978). However, there is a growing body of work investigating the biomechanical aspects of load carriage (Kinoshita, 1985; Martin & Nelson, 1986; Pierrynowski, Norman, & Winter, 1981; Quesada, Mengelkoch, Hale, & Simon, 2000). In addition, some research has been done on the effects of carried loads on maximal performance, such as times to complete either a sprint (Martin & Nelson, 1985) or an obstacle course (Holewijn & Lotens, 1992; McGinnis & Tambe, 1963). Often, load-carriage research is undertaken for the purpose of examining the effects of the weight carried and the design of the carrying equipment on the performance measures of interest (Knapik, Harman, & Reynolds, 1996). Because of test participant availability and other logistical considerations, the number of different weights carried in a single study is typically limited to three or four (Harman, Han, Frykman, & Pandorf, 2000).

A series of four load-carriage studies was conducted recently at the Center for Military Biomechanics Research in Natick, Massachusetts. Each of the studies included measures of maximal performance, energy cost, and biomechanical variables, as opposed to focusing on any one measure. The principal purpose of the studies was to compare the effects of different designs of load-carriage systems on soldiers' performance. In addition, each system was tested using three different load weights. The four studies employed the same test protocol and the basic clothing worn by the participants was the same. Each study was a repeated measures design, with a participant being tested under each load condition. The pooled data from the studies provided an unusual opportunity to examine the effects of a number of different weights on an extensive array of variables. Pearson product-moment correlation coefficients (r) were calculated to determine the relationships between carried weight and individual dependent variables. Also, the method of least squares was applied to fit simple linear regression equations to the data. The findings from these analyses of the pooled data from the four load-carriage studies are presented here.

Studies Analyzed

Summary data on the characteristics of the test participants in the four studies are shown in Table 1. Throughout testing, the participants carried a demilitarized M16 rifle and wore combat boots, a helmet, a ballistic protective vest, and a field uniform consisting of a shirt and trousers. The load-carriage equipment was added to this basic outfit. Each of the load-carriage systems was tested in a fighting, an approach, and a sustainment load configuration. The weights carried in each study are shown in Table 2. The weights include clothing and all other items on the body. Additional information on each study follows.

- *LW I vs. ALICE* (Obusek & Bensel, 1997). The first-generation prototype of the Land Warrior system (LW I) was tested against the Army's current, standard load-carriage system, the All-Purpose Lightweight Individual Carrying Equipment (ALICE). With the LW I, a rigid metal case was worn on the back as part of each load configuration. With the ALICE system, a load was carried on the back only in the approach and the sustainment configurations. Participants in this study were 12 Army enlisted men, who were infantry troops assigned to an airborne division.
- *LW II* (Obusek & Bensel, unpublished study). The second-generation prototype of the Land Warrior system (LW II) was tested in this study. As in the first-generation version of the system, every load configuration included a rigid metal case that was worn on the back. Eleven enlisted men, all infantry troops, participated in the study. Nine of the participants also took part in the LW I vs. ALICE study.
- *MOLLE vs. ALICE* (Harman et al., 1999a). A prototype system, the Modular Lightweight Load-Carrying Equipment (MOLLE), was tested against the ALICE system. With both the MOLLE and the ALICE, the approach and the sustainment configurations included a backpack, whereas the fighting load configuration did not. Participants were 12 Army enlisted women, whose military occupations varied from the physically strenuous to the sedentary.
- *MOLLE vs. MLS* (Harman et al., 1999b). This study included the MOLLE and the Modular Load System (MLS), another prototype load-carriage system. With both systems, a backpack was worn as part of the approach and the sustainment load configurations, but not with the fighting load configuration. Eleven male enlisted soldiers participated in testing. Six of the men were infantry troops and the remainder had recently completed initial Army training, which was comprised of basic and advanced infantry training.

Table 1. Mean (and *SD*) of Test Participant Characteristics

Study	Height (cm)	Weight (kg)	Age (yr)
LW I vs. ALICE	175.19 (5.65)	75.20 (13.99)	22.0 (3.1)
LW II	175.08 (4.64)	78.34 (14.57)	22.4 (3.1)
MOLLE vs. ALICE	165.92 (6.50)	61.26 (6.72)	25.3 (5.3)
MOLLE vs. MLS	179.11 (5.09)	83.46 (12.20)	24.0 (4.7)

Table 2. Mean (and *SD*) of Weights Carried (in kg)

	Load Configuration		
System	Fighting	Approach	Sustainment
LW I	23.45 (0.89)	35.47 (2.39)	50.11 (2.71)
ALICE	14.66 (0.72)	23.41 (0.73)	37.54 (1.02)
LW II	20.42 (1.18)	32.68 (1.12)	49.29 (1.29)
MOLLE	13.05 (0.63)	26.84 (0.49)	40.16 (0.60)
ALICE	11.82 (0.39)	24.07 (0.51)	38.36 (0.52)
MOLLE	12.87 (1.53)	26.18 (1.67)	40.51 (2.05)
MLS	12.26 (1.58)	24.18 (1.75)	37.65 (1.76)

Maximal Performance Test

Participants were timed as they completed a 3.2-km course, which included several small hills and consisted of paved and dirt roads. Participants were instructed to complete the course as quickly as possible. Due to equipment problems, this test was not carried out in the LW II study. In the other studies, a participant performed one run of the course in each load configuration with each type of load-carriage equipment.

The combined data of the three load-carriage studies indicate that there is a moderately strong, positive relationship between run time and weight carried, $r(190) = +.56$, $p < .01$. About 30% of the variance in time to complete the 3.2-km course is accounted for by the weight ($r^2 = .31$). The run time data and the results of the regression analysis are presented in Figure 1.

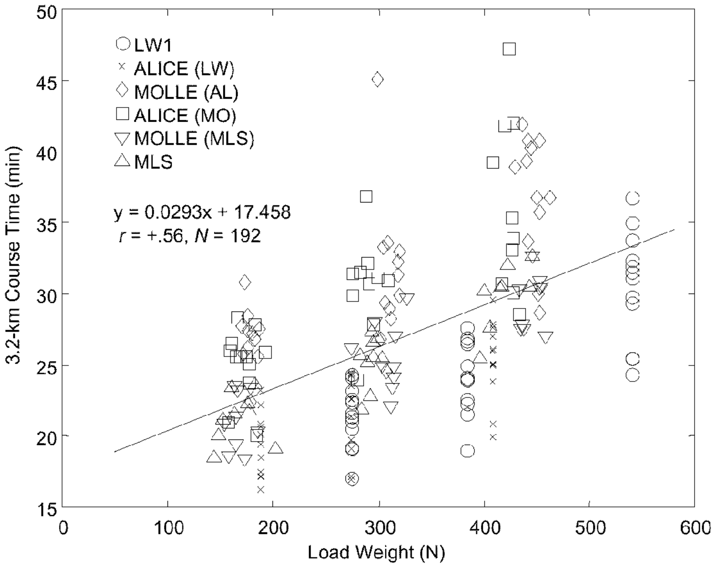

Figure 1. Scatter diagram and plot of simple linear regression equation for 3.2-km course time as a function of weight carried.

Energy Cost

Oxygen consumption was used as the index of energy cost. Test participants walked for 5 min on a level treadmill at a set speed of 4.8 km·h^{-1}. Oxygen consumption was measured at 30-s intervals during the last 1.5 min of testing. A mean was obtained over the three measurements and normalized by the participant's nude body weight. A participant had one trial in each load configuration with each type of load-carriage equipment.

The results of the regression analysis performed on the combined oxygen consumption data from all four studies are presented in Figure 2. The correlation coefficient indicates a positive and moderately strong relationship between energy cost and weight carried, $r(228) = +.63$, $p < .01$. About 40% of the variance in energy cost is accounted for by the weight ($r^2 = .39$).

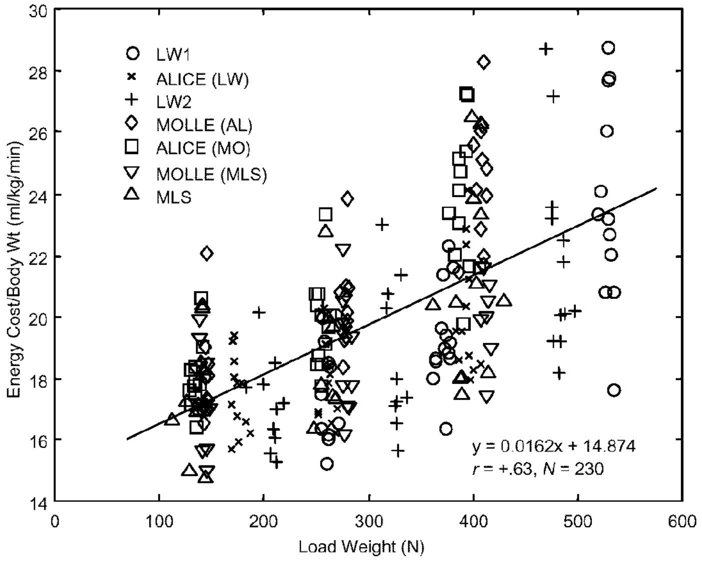

Figure 2. Scatter diagram and plot of simple linear regression equation for oxygen consumption normalized by body weight as a function of weight carried.

Biomechanics

Participants walked along a horizontal path at a controlled speed of 4.8 km·h^{-1} (± 0.2 km·h^{-1}). A force plate was mounted flush with the ground toward the end of the path. Data capture from the force plate was triggered manually about one stride before the right heel struck the plate. Force plate output was recorded for approximately 3 s at 1000 Hz. A video motion analysis system with six cameras, operating at 60 Hz, was set up in the area of the force plate. A complete stride, centered on the force plate, was analyzed from the video recordings. The body motions and the ground reaction forces were captured simultaneously. To quantify the biomechanics of walking gait, over 200 variables were measured directly or derived using customized software. The categories of kinetic and kinematic variables analyzed included ground reaction forces (GRFs), joint reaction forces, body angles, and temporal gait parameters. For the regression analyses involving the ground and the joint reaction force measures, the independent variable was system weight. System weight was defined as body weight plus the weight of the clothing and all other items on the body. The raw data entered into the regression analyses included the data from each of the trials that a participant performed in each load configuration with each type of load-carriage equipment. Depending upon the study, a participant performed from three to nine trials.

Ground Reaction Forces. The results of the regression analyses performed on the combined data of all four load-carriage studies revealed very high positive correlations between vertical GRF parameters and system weight. As an example, a scatter diagram and the best-fitting straight line for peak vertical GRF at heel strike as a function of system weight are presented in Figure 3. The r^2 value indicates that 88% of the variance in this parameter is accounted for by system weight (r^2 = .88). Correlations between some other GRF parameters and system weight are presented in Table 3, along with regression equations. As can be seen, braking and propulsive forces are highly correlated with system weight, but the correlations do not reach the values that those associated with vertical GRFs do.

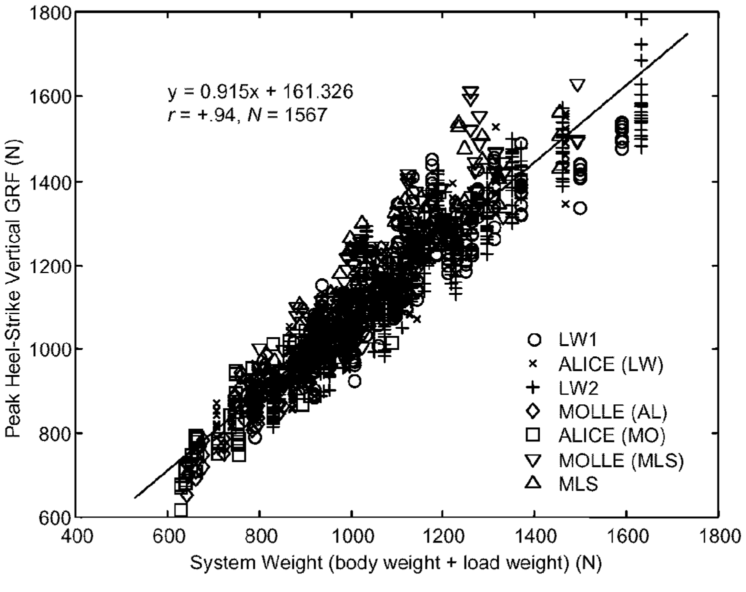

Figure 3. Scatter diagram and plot of simple linear regression equation for peak vertical GRF at heel strike as a function of system weight.

Table 3. Correlation Coefficients and Simple Linear Regression Equations for GRFs as a Function of System Weight

Variable	r^a	Regression Equation
Peak vertical force at push off	+.95*	y = 0.988x + 84.707
Peak braking force at heel strike	-.71*	y = -0.177x - 17.462
Peak propulsive force at push off	+.76*	y = 0.169x + 26.225

[a] *df* = 1565

**p* < .01

Joint Reaction Forces. Joint reaction forces at the ankle, the knee, and the hip were calculated using the inverse dynamics method. Correlations calculated on the combined data of the four load-carriage studies revealed that both the maximum force and the force averaged over the stride are very highly and positively correlated with system weight. Table 4 contains a listing of correlation coefficients, along with regression equations, for the joint reaction forces.

The slopes associated with the regressions equations for the maximum forces at the joints are steep, approaching a 1-newton increase in the joint reaction force for each 1-newton increase in system weight. Also, the slopes of the regression equations for both the maximum and the stride-averaged joint reaction forces decrease from ankle to hip. Thus, the reaction forces at the more proximal joints increased at a less rapid rate with increases in system weight than did those at the more distal joints.

Table 4. Correlation Coefficients and Simple Linear Regression Equations for Joint Reaction Forces as a Function of System Weight

Variable	r^a	Regression Equation
Max. ankle joint force	+.96*	y = 0.982x + 125.198
Max. knee joint force	+.95*	y = 0.954x - 119.615
Max. hip joint force	+.94*	y = 0.899x + 107.584
Stride-averaged ankle joint force	+.98*	y = 0.470x + 19.138
Stride-averaged knee joint force	+.98*	y = 0.460x + 19.071
Stride-averaged hip joint force	+.98*	y = 0.443x + 18.357

[a] *df* = 1565

**p* < .01

Body Angles. A number of body angles were calculated to analyze sagittal plane kinematics as affected by load weight. These are illustrated in Figure 4. For each body angle, the maximum, minimum, and range over a stride were obtained. Correlations of the body angle variables with weight carried were calculated from the combined data of the four load-carriage studies. The correlations are presented in Table 5.

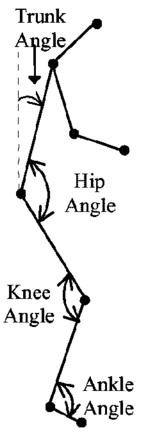

Figure 4. Definitions of body angles.

As seen in Table 5, there is a trend toward an increase in maximum ankle angle with increases in the weight carried. This finding most likely reflects an adjustment of body posture that aids in absorption of the increased GRFs at heel strike that are experienced as the load gets heavier. The increase in the range of ankle angle with increased load may be attributable to production of the greater propulsive forces needed to overcome the inertia associated with the increasing loads. The maximum knee angle and the range of knee angle decreased with increases in the weight carried. This increased knee flexion is likely to be another postural adjustment to load weight increases. Flexion at the knee improves shock absorption at heel strike and also lowers the body center of mass, making the body-plus-load system more stable. Maximum and minimum hip angles decreased and the range of hip angle increased with increases in the weight carried. The greater flexion at the hip may again aid in shock absorption. Maximum and minimum trunk angles increased with the weight carried, indicating an increased forward lean of the trunk. Trunk lean likely serves to move the center of mass of the body-plus-load forward over the base of support at the feet and also lowers the center of mass for additional stability.

Table 5. Correlation Coefficients for Sagittal Plane Body Angles and Weight Carried

	r^a		
Variable	Max.	Min.	Range
Ankle	+.13*	-.03	+.23*
Knee	-.09*	+.14*	-.23*
Hip	-.52*	-.68*	+.38*
Trunk	+.82*	+.80*	+.38*

[a] *df* = 1565 for all variables except maximum trunk angle and range of trunk angle, where *df* = 1561.
$^*p < .01$

Temporal Gait Variables. Stride frequency was one of two temporal variables analyzed using the combined data of the four load-carriage studies. Stride frequency was estimated from a single stride and was expressed as strides·s^{-1}. The other temporal variable was double support duration, which was expressed as the percentage of time during the stride cycle that both feet were in contact with the ground simultaneously.

The results of the regression analyses performed on stride frequency and double support time are presented in Figures 5 and 6, respectively.

The correlations of the temporal variables with the weight being carried are low. The correlation between stride frequency and weight carried is negative, $r(1565) = -.14$, $p < .01$, and indicates a slight trend toward decreases in stride frequency, or an increase in time to complete a stride, with increases in load. Stride velocity is the product of stride frequency and stride length. In this study, stride velocity was held constant. Thus, the decreasing stride frequency also reflects a slight trend toward increasing stride length with increases in the weight carried.

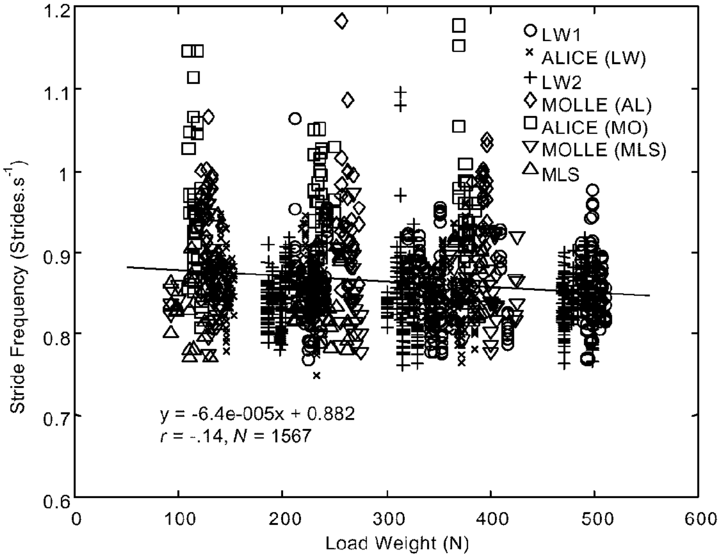

Figure 5. Scatter diagram and plot of simple linear regression equation for stride frequency as a function of weight carried.

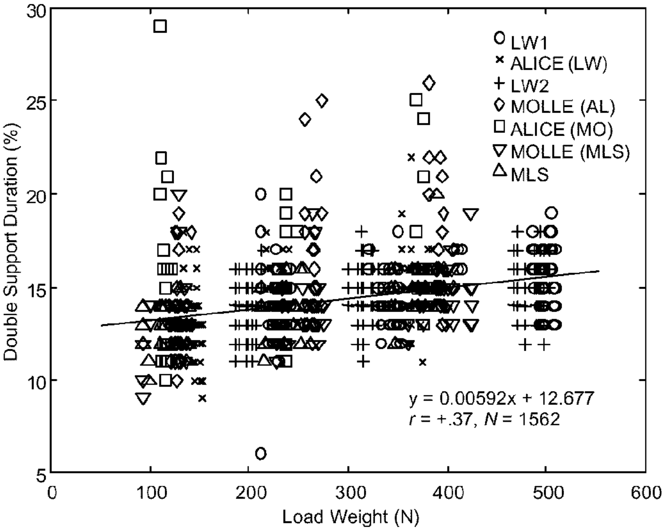

Figure 6. Scatter diagram and plot of simple linear regression equation for double support duration as a function of weight carried.

The correlation between double support duration and weight is positive, $r(1560) = +.37$, $p < .01$, and indicates that approximately 14% of the variance in double support duration is attributable to the weight carried ($r^2 = .14$). The increase in the proportion of the gait cycle spent in double support may be a means of maintaining stability with increases in load as the body should be more stable when both feet are on the ground than when one foot is in ground contact and the other is swinging forward in preparation for the next heel strike.

Discussion

As has been found in previous research (Martin & Nelson, 1985; Soule et al., 1978), the pooled data from the four load-carriage studies examined here revealed that soldiers' energy expenditure and times to complete activities requiring maximal performance increase with increases in the weight being carried. The linear regression analyses performed on the pooled data indicated that, for every 1 newton increase in weight carried, there was approximately a 3% increase in time to complete an outdoor course and a 2% increase in metabolic cost. Thus, carrying of heavy loads can result in a substantial negative impact on soldiers' mission performance and physical endurance. Furthermore, examination of the kinetics of walking gait revealed that heavy loads place a substantial burden on the load-carrier's musculoskeletal system. Regression analyses of the data from the four studies indicated that vertical ground reaction forces and joint reaction forces increased by approximately 1 newton with each 1 newton increase in system weight. The outcome of repeated exposure to these mechanical stresses associated with heavy loads can be the occurrence of acute and chronic injuries (Knapik et al., 1996).

From analyses of the kinematic variables associated with walking at 4.8 $km \cdot h^{-1}$, it appears that postural adjustments made by the load carrier mitigate the forces to which the body is subjected and aid in maintaining stability. The pooled data from the four load-carriage studies revealed a trend toward greater flexion at the knee and the hip as the weight carried increased. Thus, the knee and the hip joints may be acting as shock absorbers. There was, as well, a more pronounced forward lean of the trunk as the load carried increased, a means of keeping the body center of mass over the base of support at the feet. Temporal gait measures were also affected by the magnitude of the load carried. With increasing weight, there was a slight trend toward fewer strides per unit time. In addition, a greater proportion of the gait cycle was spent with both feet on the ground. Other researchers have reported significant increases in double support time at higher load weights (Kinoshita, 1985; Martin & Nelson, 1986) and have hypothesized that this is also a means of increasing postural stability.

The research reported here, based upon data from four load-carriage studies employing an identical testing protocol, is unusually extensive, both in the many levels of load weight and in the variety of dependent measures included. However, there are, as well, limitations in the approach taken in this work. For one, simple linear correlation and regression analyses were employed, whereas curvilinear regression analysis may have provided more insight into the relationship of the weight carried and the dependent measures investigated. In addition, total load on the body was examined, and the manner in which the weight was distributed was not considered. Furthermore, different designs of load-carriage systems were used in the different studies, and analyses were carried out in the individual studies to assess design effects. However, the effects of system design and possible interactions between weight carried and system design were not investigated in the analyses of the pooled data reported here. Finally, the participants in the studies had not engaged in strenuous physical exercise prior to data-collection sessions. Soldiers in the field often carry loads for prolonged periods of time. Testing of soldiers under such conditions may lead to a fuller understanding of the impact of load weight on performance.

Conclusion

The weights soldiers carry have substantial negative effects on physical performance and endurance, as well as on the likelihood of injury. Postural adjustments are made to mitigate the negative consequences of heavy loads. A greater understanding of the implications of weight on military operations and the well-being of soldiers may be gained from the study of soldiers engaged in prolonged periods of load carrying.

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