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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

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13. ABSTRACT (Maximum 200 words) The experiment evaluated the physiological, biomechanical, and maximal performance responses of 12 female soldiers carrying loads with prototype Modular Lightweight Load-Carrying Equipment with Interceptor body armor (MOLLE/I), and All-Purpose Lightweight Individual Carrying Equipment with PASGT body armor (ALICE/P). MOLLE/I and ALICE/P did not differ on several tests including: energy cost of load carriage, 2 mile load carriage speed, sprint speed with load, knee range of motion, and heel-strike braking force. The ALICE/P bested MOLLE/I for speed of getting prone and standing; speed of getting prone, rolling 3 times, and aiming a rifle; obstacle course speed, especially for the low crawl; grenade throw distance; subjective comments; total-body complaints under the fighting load; heel-strike and push-off forces; front-back pack movement; and pressure under the shoulder straps. MOLLE/I bested ALICE/P as to design modularity; walking posture; quick pack release; tightness of shot groups; shoulder complaints; complaints about all body areas other than the shoulders and hips under the sustainment load; total-body complaints under the approach and sustainment loads; time in double-support under the approach and sustainment loads; front-back trunk sway under the sustainment load; and horizontal location of pack center of mass under the sustainment load. Despite its overall superiority, the prototype MOLLE/I could be improved to enhance obstacle course performance, make its quick-release system easier to find and reach, enhance body armor comfort and fit for females, reduce its restrictiveness, and reduce interference with tightening the waist belt. Frame cracking of MOLLE prototypes has apparently been solved by improved manufacturing techniques.				
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BACKGROUND

In 1994, the U.S. Army and U.S. Marine Corps conducted front-end analyses (FEAs) on individual load-carrying equipment and individual body armor. The purpose of the FEAs was to make a comprehensive evaluation of overall requirements of the Army and Marines, and determine where current technology could lead in design and performance. Upon completion of the FEAs, the U.S. Army Infantry Center wrote an operational requirements document for modular body armor (MBA) and a Modular Load System (MLS). The acquisition strategy specified by the Project Manager-Soldier (PM-Soldier) was to solicit a contract for the design and production of MBA and MLS as an integrated system. The Marine Corps Program Manager-Combat Support and Logistics Equipment had a need to field body armor and load-carriage equipment more rapidly than the MBA/MLS schedule allowed and therefore conducted a separate development program with a government design for body armor and load-carriage equipment. In an effort to minimize duplication of development costs, gain economy of scale, and standardize, the Army and Marines tested each other's MBA/MLS prototypes in order to determine if one system could be developed for use by both services. USARIEM conducted a study on male soldiers comparing the Army and Marine MBA/MLS systems (4). As a result of that study, and field test evaluations, the Army decided to discontinue the MBA/MLS contract it initiated, and instead join in development of the Marines' MBA/MLS, which was designated Modular Lightweight Load-Carrying Equipment (MOLLE), used in conjunction with Interceptor body armor. The MBA/MLS Operational Requirements Document (ORD) requires these systems to be used by both male and female soldiers. Because it had been initially evaluated on male soldiers only, this study was initiated in order to compare the effectiveness of the MOLLE/Interceptor to that of the currently used U.S. Army All-Purpose Lightweight Individual Carrying Equipment (ALICE) among female soldiers. The study was funded through the U.S. Army Soldier Systems Command (USASSCOM). It compared the physiological, biomechanical, and maximal performance effects of both systems on soldiers carrying light, medium, and heavy loads.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

ALICE	All-purpose lightweight individual carrying equipment
BDU	Battle dress uniform
DCM	Average distance from center of mass of the target (marksmanship test)
FEA	Front end analysis
LED	Light emitting diode
MBA	Modular Body Armor
MLS	Modular Load System
MOLLE	Modular Lightweight Load-carrying Equipment designed by the U.S. Army Soldier Systems Command, manufactured by Specialty Plastics Products, and tested in the experiment described herein
MOS	Military Occupational Specialties
ORD	Operational Requirements Document
psi	Pounds per square inch
SGT	Shot group tightness (marksmanship test)
STIME	Sighting time; the time between LED illumination and trigger pull (marksmanship test)
USARIEM	U.S. Army Research Institute of Environmental Medicine
USASSCOM	U.S. Army Soldier Systems Command, Natick, MA
% HITS	Target hits as a percentage of total shots (marksmanship test)

DISCLAIMER

The conclusions, recommendations, and any other opinions expressed in this report are those of the authors alone and do not reflect the opinion, policy, or position of the Department of the Army or the United States Government.

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EXECUTIVE SUMMARY

The experiment evaluated the physiological, biomechanical, and maximal performance responses of female soldiers carrying light, medium, and heavy loads using the prototype U.S. Marine Corps Modular Lightweight Load-Carrying Equipment (MOLLE) with Interceptor body armor, and the currently used U.S. Army All-Purpose Lightweight Individual Carrying Equipment (ALICE) with PASGT body armor. Twelve female soldiers were tested as they carried "fighting," "approach," and "sustainment" loads. Physiological evaluation determined the rate of oxygen consumption for carrying loads with each system/load combination. Biomechanical analysis quantified gait and posture, pack stability, pack center of mass, joint reaction forces of the lower extremities, and pack contact pressures at the shoulder straps and waist-belt. Maximal performance evaluations were made on a variety of typical soldier tasks. Comfort and functionality questionnaires were administered. All testing was performed at USASSCOM in Natick, MA, during the Spring of 1998.

The MOLLE and ALICE did not differ as to any variables not specified below. Some examples: energy cost of load carriage, speed of carrying loads 2 miles, speed of sprinting with a load, knee range of motion, and heel-strike braking force. **The ALICE showed advantage over the MOLLE as to** speed of getting prone and returning to standing; speed of getting prone, rolling laterally three times, and aiming a rifle; obstacle course speed, especially for the low crawl; grenade throwing distance; number of positive and negative subjective comments; number and severity of total-body complaints under the fighting load; heel-strike and push-off forces; front-back pack movement; and pressure under the shoulder straps. **The MOLLE showed advantage over the ALICE as to** modular flexible design; upright walking posture; quick pack release; tightness of marksmanship shot groups; number and severity of shoulder complaints; number and severity of complaints about all body areas other than the shoulders and hips under the sustainment load; number and severity of total-body complaints under the approach and sustainment loads; time in double-support under the approach and sustainment loads; front-back trunk sway under the sustainment load; and horizontal location of pack center of mass under the sustainment load.

Despite its innovative design, the prototype MOLLE could be improved, particularly as to enhancing obstacle course performance. Its quick-release system could be made easier to find and reach. The Interceptor body armor needs improvement to enhance comfort and facilitate soldier tasks. A problem of frame cracking in the MOLLE prototypes has apparently been solved by improved manufacturing techniques, as demonstrated by field testing subsequent to our experiment.

A problem with both systems was that, when body armor was worn, the waist-belt could not be cinched tightly enough to readily transfer weight from the shoulders to the hips. The Interceptor armor used with the MOLLE was particularly loose around the waist, accentuating the problem of tightening the hip belt, and allowing too much load movement when the armor was worn without the pack to keep it in place. The waist of the body armor could likely be made considerably smaller without being too tight. Women appear to need more specific sizing of the armor vest than do males because of greater variability in chest-waist-hip ratios.

INTRODUCTION

The All-Purpose, Lightweight, Individual, Load-Carrying Equipment (ALICE) was type-classified in 1973 and is still standard-issue load-carriage equipment in both the U.S. Army and Marines. Recently, both services recognized the need for new load-carriage and body armor systems that would comprise a fighting vest, body armor, and a modular backpack that could be quickly jettisoned without removing the body armor or fighting load. Toward that end, the Army funded the MLS/MBA program to develop a Modular Load System (MLS) and modular body armor (MBA). The Marines funded the development by USASSCOM of a similar system called Modular Lightweight Load-Carrying Equipment (MOLLE), used in conjunction with Interceptor Body Armor. Both services recognized the advantages of testing both systems, including risk reduction to test volunteers and minimization of duplicated effort. In keeping with that goal, the U.S. Army Soldier Systems Command (USASSCOM) funded a study by USARIEM to compare the Army and Marine MBA/MLS systems among male soldiers (4). The results of that study and several different field evaluations prompted the decision to discontinue further development of the Army's MBA/MLS, and develop the MOLLE for both services. Because the system was initially evaluated on male soldiers only, the MOLLE had to be evaluated on female soldiers as well. The purpose of this study, funded through the USASSCOM, was to compare the effectiveness of the MOLLE to that of the currently used U.S. Army All-Purpose Lightweight Individual Carrying Equipment (ALICE) among female soldiers. The study compared the physiological, biomechanical, and maximal performance effects of both systems on female soldiers carrying light, medium, and heavy loads.

The loads selected for this study are supported by the U.S. Army field manual on foot travel (2). It states that up to 72 lb may be carried on "prolonged dynamic operations" and that "circumstances could require soldiers to carry loads heavier than 72 lb, such as approach marches through terrain impassable to vehicles or where ground/air transportation resources are not available. These ... loads can be carried easily by well-conditioned soldiers. When the mission demands that soldiers be employed as porters, loads of up to 120 lb can be carried for several days over distances of 20 km a day" and "loads of up to 150 lb are feasible." Soldiers in actual combat operations have often reported carrying loads well in excess of 100 lb.

METHODS

It should be noted that, in this experiment, the MOLLE system was always tested in conjunction with the Interceptor body armor, and the ALICE system was always tested in conjunction with the PASGT body armor. Thus in this report, the term MOLLE refers to MOLLE/Interceptor combination, while the term ALICE refers to ALICE/PASGT combination.

RESEARCH VOLUNTEERS

Twelve female volunteers of varying Military Occupational Specialties (MOS's) (6 from Fort Carson, CO, and 6 from Fort Drum, NY) were tested to compare the MOLLE/Interceptor and ALICE/PASGT systems. Because women are currently not allowed into ground combat units, none were combat soldiers. Several had sedentary jobs, but more physically demanding MOS's were represented as well, including the Military Police. Table 1 shows some basic information about the volunteers. The maximal oxygen uptake data was from testing described later in this section.

Table 1. Vital statistics of the volunteers (n=12, all female), mean(SD).

Volunteer Number	Height (cm)	Body Mass (kg)	Age (years)	VO2 max (ml $\times$ min ⁻¹ $\times$ kg ⁻¹)
1	163.8	63.1	29.1	53.4
2	170.9	66.2	22.9	53.8
3	157.6	51.3	38.2	45.3
4	151.0	54.6	22.4	48.6
5	167.5	62.7	28.0	54.4
6	157.9	52.7	19.4	43.6
7	172.4	70.3	24.6	43.6
8	159.9	66.6	20.7	54.2
9	156.5	54.0	20.4	46.8
10	163.4	51.2	20.6	51.4
11	158.4	58.5	27.6	48.9
12	170.3	61.6	30.0	41.9
mean $\pm$ SD	162.5(6.4)	59.4(6.3)	25.3(5.3)	48.8(4.6)

The principal investigator or an assisting investigator briefed all potential research volunteers. Informed consent was obtained from those who chose to volunteer. The volunteers participated in the experiment for approximately 3 weeks, with 1 or 2 test sessions a day lasting between 1 and 3 hours each, which included testing, waiting for other volunteers to be tested, and resting between trials. The volunteers were trained and tested in and around the U.S. Army Research Institute of Environmental Medicine (USARIEM) located on the grounds of the USASSC.

THE TEST BATTERY

Test Conditions and Loads

The volunteers were tested with three different loads. The "fighting load" consisted of the battle dress uniform (BDU), boots, body armor, kevlar helmet, equipment belt, load-carriage vest, dummy grenades and ammunition clips, and dummy M-16 rifle. The "approach load" included the fighting load plus 20 lb of weight in a backpack, while the "sustainment load" included the fighting load plus 50 lb of weight in the backpack. The weight in a pack consisted of steel plates, sandbags, or containers

filled with small metal pieces, held at the pack center-of-volume with foam blocks. Weights of all clothing and equipment carried by the volunteers are indicated in Table 2. The term "skin-out" means that the weight of everything worn or carried by the volunteer (e.g. socks, undergarments) is included. The variability in weight carried reflects differences in weight of the two pack/body armor systems, and differences in size among the volunteers.

Table 2. Weights ("skin-out," lb., mean $\pm$ SD) carried by the volunteers.

Load	ALICE/PASGT	MOLLE/Interceptor
Fighting	37.2 $\pm$ 2.2	38.6 $\pm$ 1.0
Approach	63.5 $\pm$ 1.8	67.9 $\pm$ 2.0
Sustainment	94.0 $\pm$ 1.4	98.8 $\pm$ 1.6

For each type of test, the order in which the different system/load combinations were presented was different for different volunteers, and was systematically balanced so that testing order did not bias the results. Table 3 summarizes the tests administered. The reason that all system/load combinations were not used for all tests was based on the appropriateness of the system and load for the simulated situation. The sustainment load is not carried when battle is close at hand. Thus the sustainment load was not used for the simulated maneuvers that might occur when at or near the battlefield. In actual combat, the approach load is not carried. Thus the approach load was not used for the simulated combat maneuvers such as rifle-firing or grenade-throwing. Maximum oxygen uptake testing and anthropometry were done, as usual, without a load.

Table 3. The tests administered.

		MOLLE/Interceptor			ALICE/PASGT		
Test Procedure	Basic Clothing only	Fighting Load	Approach Load	Sustainment Load	Fighting Load	Approach Load	Sustainment Load
anthropometry	+						
max oxygen uptake	+						
energy cost		+	+	+	+	+	+
biomechanics		+	+	+	+	+	+
2 mile course		+	+	+	+	+	+
disencumber			+			+	
prone and stand		+	+		+	+	
obstacle course		+	+		+	+	
prone and roll	+	+			+		
marksmanship	+	+			+		
grenade throw	+	+			+		

Physiological Testing

Maximal Oxygen Uptake. For this test, oxygen uptake was measured using a continuous, uphill, speed-incremental, treadmill protocol and a computerized expired-gas collection, analysis, and display system custom-developed at USARIEM. To ensure the safety of the volunteer, the output of a single lead (V_5) electrocardiograph was monitored during the entire test by trained personnel. The volunteer, positioned atop a treadmill, was connected to the gas collection apparatus via a mouthpiece, large 2-way, Hans Rudolph valve, and flexible tubing supported by headgear and overhead support arm. The gas analysis system incorporated an air-flow meter, thermistor, oxygen analyzer, carbon-dioxide analyzer, electronic square wave counter, and Hewlett-Packard desktop computer and printer which determined and printed out at pre-selected intervals the rate of oxygen consumption and ventilation per minute expressed both in absolute terms and relative to the individual's body mass. The volunteer first warmed up by running for 5 minutes at 5 miles per hour with the treadmill bed horizontal. After a 5 minute rest off the treadmill with mouthpiece removed, the volunteer remounted the treadmill, reattached the mouthpiece, and started running on a 5% uphill grade at a speed determined to be moderate based on her heart rate during the warm-up run. For the remainder of the test, the mask was kept on continuously and oxygen uptake was calculated every 30 seconds. Every 2 minutes, the treadmill speed

was increased by 0.5 mile/hr without changing the treadmill grade. A volunteer was considered to be at maximal oxygen uptake if, 1 minute after a speed increase, she had not increased oxygen uptake by at least $2.0 \text{ ml} \times \text{min}^{-1} \times \text{kg}^{-1}$. The volunteers generally reached maximum oxygen uptake on the treadmill within 10-12 minutes.

Energy Cost. In order to estimate energy consumption, oxygen uptake was measured using the same system as for the maximal oxygen uptake tests, while the volunteer walked on a level treadmill at 3.0 mph, carrying the fighting, approach, and sustainment loads, using each of the two different load-carriage systems, for a total of six load-carriage conditions. The walking duration per test speed was about 5-6 minutes to allow the volunteer to reach steady-state oxygen uptake. During the last 2 minutes of walking under each load-carriage condition, the volunteer put on her mask and oxygen uptake calculations were made every 30 seconds.

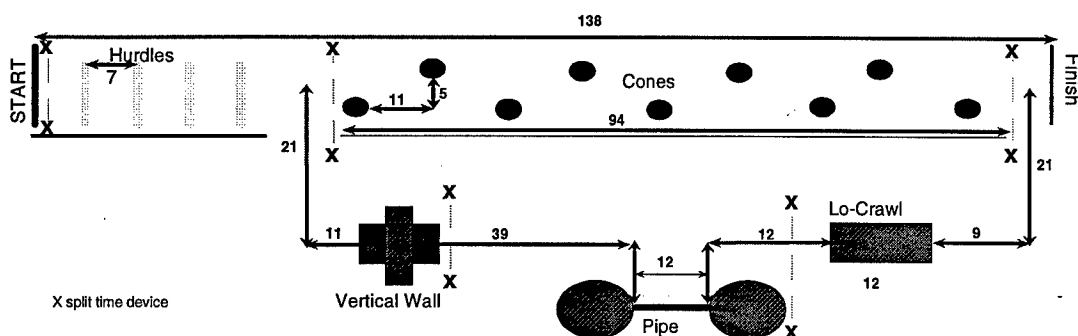
Performance Testing

One of the most critical factors to be considered in evaluating soldier/equipment interaction is the effect of the equipment on soldier task performance in scenarios involving the preparation for and engagement in combat. The tests below were designed to simulate battlefield activities that might be affected by load-carriage system.

Timed Tests. Because the speed with which a soldier can perform a task can greatly affect the outcome of battle, one means of evaluating the soldier/equipment interaction is to time how long it takes the soldier to complete challenging tasks while using the equipment. Thus, the research volunteers were timed on the following tasks while carrying the loads indicated. Before they performed the events, they were trained in proper technique and afforded time to practice, thereby improving consistency and minimizing the risk of injury. Each volunteer

- covered at maximal speed a 2-mile paved course which included four small hills. She performed this test while carrying the fighting, approach, and sustainment loads using each of two different load-carriage systems for a total of six load-carriage conditions.
- walked at normal marching speed and, after a verbal signal from the experimenter, completely removed the backpack and dropped to a prone position on the ground. She performed this test with the approach load using each of two different load-carriage systems for a total of two load-carriage conditions.
- walked at normal marching speed and, after a verbal signal from the experimenter, dropped to a prone position on the ground then stood back up. This test was performed using no pack at all, and under the fighting and approach loads with each of two different load-carriage systems for a total of five load-carriage conditions.

- walked at normal marching speed, and after a verbal signal from the experimenter, dropped to a prone position on the ground, rolled laterally three full revolutions, and took aim with the rifle. This test was performed with BDU only and with the fighting load using each of the two systems for a total of 3 conditions.
- negotiated a 6-station obstacle course (Figure 1) using the fighting and approach loads with each of two different load-carriage systems for a total of four load-carriage conditions. The obstacle course included:
 - a set of five 18 in high plastic hurdles
 - a zigzag of rubber cones, 88 ft long and 5 ft wide
 - a crawl space of wood/wire, 24" high, 36" wide, and 12 feet long
 - a horizontal shimmy pipe, 12 feet long
 - a 54" high sheer wooden wall without footholds or ropes
 - a 60 foot straight run



*Notes: first time through cone section zig zag run, second time straight run.
units = feet.

Figure 1. Obstacle course

Times were obtained for each course segment using a light-beam system with telemetry (Brower Timing Systems, Salt Lake City, UT).

Grenade Throw. According to the Soldier's Manual of Common Tasks (3), a soldier should be able to throw a hand grenade to within 5 m of a selected point 35 m away. Thus, we tested the accuracy with which the volunteers could hit such a target with a dummy hand-grenade, about the same weight (one lb) as a real grenade. Each volunteer threw from a standing position towards a 5-meter diameter target 35 m away. Both the number of hits and the distance from the center of the target were recorded. The volunteers were tested in BDU only and with the fighting load using each of the two systems for a total of three conditions. Five trials were performed for each condition.

Rifle Marksmanship. The rifle marksmanship of the volunteers was tested on a Noptel ST-1000 laser marksmanship simulator (Noptel, Oy; Oulu, Finland). They shot while

they wore BDU only and while they wore the fighting load using each of the two load-carriage systems for a total of three conditions. The simulator consists of a laser transmitter, an optical glass laser-sensitive receiver with an associated paper aiming target, a personal computer, manufacturer supplied software, and a disabled M16A1 rifle. The laser transmitter emits a continuous 0.55 mm amplitude 0.8 mm wavelength beam, which is invisible to the eye, that allows aiming positions to be monitored and recorded throughout the sighting and shooting process. A vibration sensor in the laser unit detects when the weapon is dry-fired. Shot location is recorded via the position of the laser on the optical glass laser sensor. The target used was a 2.3 cm diameter circular target located 5 m from the shooter. This simulated a 46 cm diameter target at 50 m, which is similar to the standard 49 cm wide, "100-m military silhouette man" used on training and qualifying ranges for the U.S. Army. Volunteers were tested for marksmanship speed and accuracy. During assessment, volunteers shot from two positions: the prone unsupported position (i.e., no sandbags or other support except for the ground) and the free-standing unsupported position. Following a verbal "ready" signal and a random 1-10 second preparatory interval, a red LED positioned on the lower left of, and 16 cm from the target was illuminated as the signal to shoot. The volunteer fired at the target as quickly as possible while trying to maintain accuracy. A total of 10 shots or "trials" were taken in each shooting position. Each trial consisted of waiting for the light, sighting the target and pulling the trigger; thus multiple shots were not fired upon a single illumination of the red light. When in the prone position, volunteers were instructed to hold the rifle low enough to enable them to see the stimulus light from above the rifle's sights. In the free-standing unsupported position volunteers were required to hold the barrel of the rifle below the waist while waiting for the stimulus light to come on and then aim and fire the weapon.

Volunteers were tested in the BDU and helmet, and with the two different load-carriage systems for a total of three conditions. Familiarization with the Noptel system was provided prior to actual data collection. The volunteers had received the standard Army marksmanship training required of all soldiers. Familiarization with the laser simulator and the testing procedure consisted of two sessions of a minimum of 30 shots per condition. Some additional training was provided to volunteers whose scores were not consistent. At the end of the test session, volunteers were also verbally asked "Do you have any comments regarding shooting under these three equipment conditions?" Volunteers' comments were recorded and compiled.

Marksmanship variables were assessed for groups of five shots. These variables included the average distance from center of mass of the target (DCM); shot group tightness (SGT); sighting time (STIME) which was the time from when the red LED light came on to trigger pull; and percentage of targets hit (% HITS). DCM and SGT were calculated, using custom-written software, from the Noptel point and sector scores (11). Actual values for DCM and SGT can be multiplied by 20 to give simulated full-scaled target measures.

At the end of the test session, volunteers were given a four-item questionnaire that included questions about the positive and negative effects the volunteers felt the different load-carriage systems had on their shooting. They were also asked which system they

would choose if they had a choice, and for suggested improvements to the load-carriage systems.

Comfort

The comfort of the different load-carriage systems was assessed by having the volunteers fill out a "Physical Discomfort Questionnaire" (Appendix A) following each maximal speed 2-mile load-carriage run.

Biomechanical Testing

Kinematics and Kinetics. The volunteers walked at 3 miles per hour across a force platform, within the field of view of six Qualisys cameras (Glastonbury, CT) while carrying the fighting, approach, and sustainment loads using each of two different load-carriage systems for a total of six load-carriage conditions. Biomechanical analysis of the camera data was performed using both Qualisys and custom software.

During the biomechanical testing, volunteers wore the standard Army physical training uniform, consisting of the gray T-shirt and shorts with combat boots. Spherical reflective markers approximately 1 inch in diameter were affixed to the skin (or boot) using double sided tape. Markers were placed on the right side of the body at the base of the 5th metatarsal, lateral malleolus of the ankle, lateral femoral condyle of the knee, greater trochanter of the hip, acromion process of the shoulder, zygomatic arch of the head, lateral epicondyle of the elbow, and the radial styloid process of the wrist.

An additional marker was placed at the location of the sagittal plane center of mass of the pack in each pack/load configuration. The sagittal plane center of mass location was determined in each pack/load configuration by placing the loaded pack, the vest, and the ballistic protective vest on a lightweight, foam torso dummy and using a standard balance board technique.

Volunteers walked along a level, 15-foot walkway at 3.0 miles/hr paced by a custom-built system that cued the volunteer to the appropriate walking speed with a striped cord moving at 3.0 miles/hr located next to the walkway. The M16A1 mockup was carried at port arms. An electronic timing device insured that volunteers walked across the force plate at 3.0 miles/hr $\pm$ 5%. Trials during which the walking speed was not between 2.85 miles/hr and 3.15 miles/hr were discarded, and the trial was repeated. A video motion analysis system (Qualisys, Glastonbury, CT) using six cameras recorded the body movements of the volunteers in three dimensions as they walked across a force plate (AMTI, Watertown, MA) embedded flush with the floor. The sampling frequency of the cameras was 60 Hz. The force plate recorded the ground reaction forces as the volunteer stepped on the plate. The sampling frequency of the force plate was 1,000 Hz. Three walking trials were conducted for each system/load configuration. All six experimental conditions were tested in a single session, with the volunteers resting between trials as needed and having a 15-min rest break after each block of trials.

Under the assumption of bilateral symmetry, segmental movement data for the left side of the body was generated by phase shifting the right side data by 180°. A 12-segment model of the human body was constructed (2 feet, 2 shanks, 2 thighs, 2 forearms, 2 upper-arms, a trunk and a head), and the mass inertial properties of the segments were taken from estimates given by Dempster (1). A custom-written software program performed a standard link segment analysis frame-by-frame for a single stride. The single stride selected for analysis was centered on the point when the right foot struck the force plate. The stride was defined as that portion of the gait cycle from the point in time at which the right foot crossed in front of the left leg to the point in time at which the right foot next crossed in front of the left leg. The custom program calculated the location of the body center of mass as described by Winter (13) and plotted its coordinates for each frame of video data. The program also determined stride length, stride frequency, and body segment displacements, velocities, and accelerations. Joint reaction forces at the ankle, knee, and hip joints were calculated using inverse dynamics.

The vertical and horizontal distances between the load center of mass and the body center of mass were calculated for each frame during the stride. The mean vertical and horizontal distances over the entire stride were then calculated from the frame-by-frame data for a trial. These mean values are given as the vertical and horizontal distances for that trial.

For each frame of video data, the coordinates of a reference point on the trunk were calculated as the midpoint of a line segment connecting the right and left shoulders. The vertical and horizontal distances between the pack center of mass and the trunk reference point were then calculated for each frame during the stride. The relative motion between the pack and the body in the vertical and horizontal planes was assessed by calculating the standard deviations of the pack-to-trunk reference point vertical and horizontal distances, respectively, over the stride. The standard deviations of the mean vertical and horizontal distances calculated from the frame-by-frame data are given as the relative pack motion for a given trial.

The maximum and minimum trunk, hip, knee, and ankle angles were also determined (Figure 2). The trunk angle was defined as the angle between the trunk segment and the vertical axis. For a subject facing towards the right, the trunk angle is positive measured clockwise from the vertical and negative measured counter-clockwise from the vertical. The hip angle was defined as the angle between the thigh segment and the plane defined by the segment connecting right and left hips with the trunk segment. The knee angle was defined as the angle between the thigh and shank segments, and the ankle angle was defined as the angle between the shank and foot segments.

Because the duration of a single stride varied among subjects, it was necessary to normalize the differing time scales to allow for the direct comparison of the timing of

events within the gait cycle across subjects. This was accomplished by expressing the time course of all the biomechanical variables as a percentage of the stride cycle.

Pack Contact Pressure. The pressures on the shoulders and hips associated with each system/load configuration were measured by placing Tekscan pressure sensor pads (Tekscan, Boston, MA) under the pack straps and back contact area. The sensors are made of thin, flexible, 10.2 cm x 22.9 cm Mylar with a force transducer for each square centimeter. The pressure sensor sampling frequency was 60 Hz. The computerized Tekscan analysis system was used to determine the localized skin contact pressures placed on the research volunteer in all six experimental conditions. The video and force plate data collection was synchronized with the Tekscan data collection through the use of a common triggering switch. Pack contact pressures are expressed as both the array average (the mean of all individual sensor values including those which recorded zero pressure for each pad over the entire stride) and the array maximum (the maximum individual sensor value recorded for each pad over the entire stride).

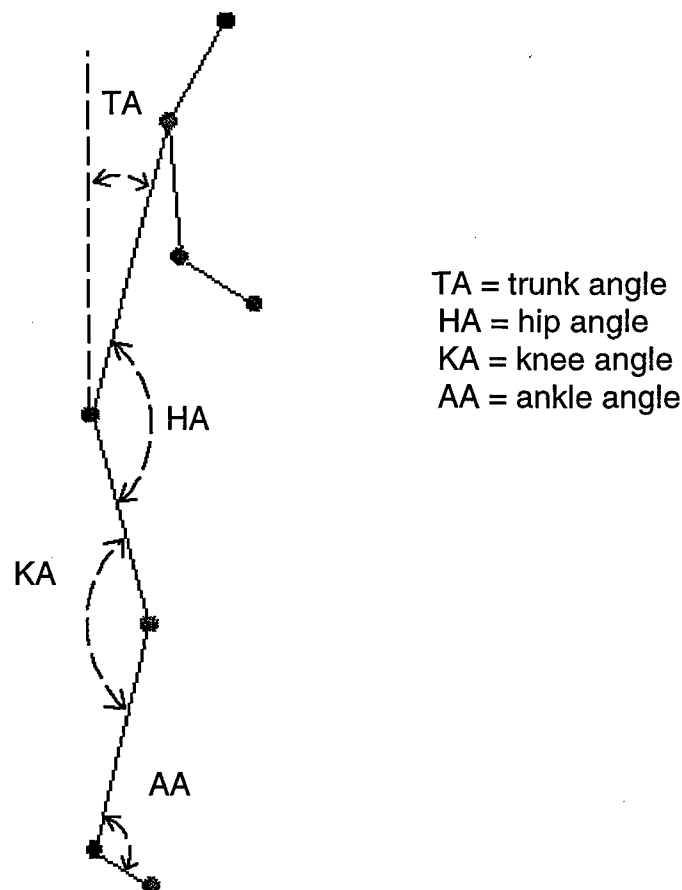


Figure 2. Definition of joint angles

Anthropometry

In order to determine how body proportions relate to the way in which the pack is carried and to the effectiveness of the backpack frame/waist-belt system, body measurements were made including:

<Circumferences>

waist, hips, thigh, calf

<Diameters>

shoulders, hips, knees, ankles

<Lengths>

trunk, upper leg, lower leg

<Skinfolds>

back, arm, abdomen, thigh

STATISTICAL ANALYSIS

The results were analyzed using 2-way analysis of variance (ANOVA) to examine the effects of system and load on all dependent variables. A p-value of 0.05 was considered indicative of a statistically significant difference between loads or systems, and of a statistically significant interaction of system and load. When ANOVA identified a significant load effect for a given dependent variable, the Duncan post-hoc procedure was used to identify which loads differed from each other.

RESULTS

It should be noted that, in this section and throughout the report, the term MOLLE refers to MOLLE/Interceptor combination, while the term ALICE refers to ALICE/PASGT combination.

ENERGY COST

Table 4 shows that oxygen consumption relative to body mass increased significantly with the load carried, but there was no significant or notable difference between load-carriage systems. This indicates that neither system was better as to the energy cost of load carriage.

Table 4. Oxygen consumption relative to body mass (ml/kg/min), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	18.05 ^c (1.47)	20.29 ^b (1.38)	24.34 ^a (2.06)
ALICE	17.95 ^c (1.09)	19.79 ^b (1.49)	23.77 ^a (2.31)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Oxygen consumption was calculated relative to the mass of the body plus the load. As seen in Table 5, the energy cost calculated this way did not differ significantly between the load-carriage systems, nor between the fighting and sustainment loads. However, the energy cost of carrying the approach loads was significantly lower, on the order of 5%. Somehow, the women were more efficient carrying the approach load than either the fighting or sustainment loads which were respectively lighter and heavier. The reason for greater efficiency with the approach load cannot be determined at this time.

Table 5. Oxygen consumption relative to total mass (ml/kg/min), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	14.53 ^a (1.18)	13.83 ^b (0.96)	14.44 ^a (1.05)
ALICE	14.63 ^a (0.87)	13.84 ^b (1.03)	14.35 ^a (1.22)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Based on the percentage of maximal oxygen consumption used during load carriage (Table 6), the aerobic requirement was not very high for carrying any of the loads at 3 miles per hour, ranging from about 37% of maximum for the approach load to

about 50% of maximum for the sustainment load. The percentages did not differ to a significant or notable degree between load-carriage systems.

Table 6. Percentage of maximum oxygen consumption, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	37.25 ^c (4.28)	41.88 ^b (4.61)	50.37 ^a (7.02)
ALICE	37.05 ^c (3.92)	40.87 ^b (4.75)	49.18 ^a (7.44)

Values superscripted with different letters are significantly ($p < 0.05$) different.

TIMED TESTS

Table 7 shows that, while there were significant differences among the times required to carry the fighting, approach, and sustainment loads at maximal speed over 2 miles, there was no difference between the time required to carry the same load using the ALICE versus MOLLE. Volunteers moved 14%-18% slower with the approach load than with the fighting load, and 27%-31% slower with the sustainment load than with the fighting load.

Table 7. Time (min) to cover 2 miles on foot, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	26.89 ^c (2.06)	31.35 ^b (5.13)	36.96 ^a (4.31)
ALICE	25.08 ^c (2.47)	30.63 ^b (3.28)	36.19 ^a (6.13)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 8 shows that, while there were significant differences in time required to get prone and return to standing between the fighting and approach loads, there was no significant difference between the time required when carrying the same load using the ALICE versus MOLLE. The non-significant 8% longer time for the MOLLE may be related to its higher center of mass. Packs with higher center of mass tend to slow a subject trying to rise from the prone position because of the longer moment arm of the load about the feet. Also, volunteers learned to dive to the ground more slowly with the higher pack in order to prevent the top of the pack from hitting the back of the helmet.

Table 8. Time (s) to get prone and return to standing, mean (SD).

	Fighting Load	Approach Load
MOLLE	3.55 ^b (0.73)	5.04 ^a (0.74)
ALICE	3.28 ^b (0.51)	4.66 ^a (0.74)

Time without carrying a load: 2.37^c (0.23)

Values superscripted with different letters are significantly ($p<0.05$) different.

The volunteers were tested with the approach load only as to the time required to remove the pack and get prone (Table 9). The volunteers were on average 31% faster with the MOLLE, a significant difference, presumably because of the MOLLE's quick release straps, which they pulled as they fell forward, thereby letting the pack drop backwards. Yet the volunteers sometimes had difficulty in rapidly locating the quick-release straps on the MOLLE, causing delay in pack removal.

Table 9. Time (s) to remove pack and get prone.

	Approach Load
MOLLE	2.82 ^b (0.82)
ALICE	3.69 ^a (1.02)

Values superscripted with different letters are significantly ($p<0.05$) different.

Table 10 shows that the differences in time taken to hit the ground, roll three times, and aim the rifle did not differ significantly between test conditions, although the mean time for the MOLLE was 7% longer. The loose fit of the Interceptor body armor may have had some slowing effect on the volunteers.

Table 10. Time (s) to get prone and roll three times, mean (SD).

	No Load	MOLLE Fighting Load	ALICE Fighting Load
Time (seconds)	5.11 ^a (1.01)	5.49 ^a (0.89)	5.12 ^a (0.81)

Values superscripted with different letters are significantly ($p<0.05$) different.

There were several trials in which the female volunteers could not successfully complete the entire obstacle course. The two most difficult stations were the horizontal pipe and the 54" high wall. With the fighting load, 78% of the women negotiated the full length of the pipe with the ALICE and 82% with the MOLLE. However, with the approach load, only 27% of the volunteers made it across the pipe with the ALICE, and

33% with the MOLLE. The volunteers had even more trouble negotiating the wall. With the fighting load, 56% of the women made it over the wall with the ALICE and 55% with the MOLLE. With the approach load, only 36% of the volunteers made it over the wall with the ALICE, and 11% with the MOLLE. To avoid basing comparison of total obstacle course times on the scores of just the volunteers who completed the whole course under every pack condition, the total obstacle course times shown in Table 11 are for the complete course minus the pipe and wall, the times for which are reported separately in subsequent tables.

As one would expect, the approach loads took significantly longer than the fighting loads. There were no significant differences in time between the load-carriage systems. However, the volunteers averaged 10% longer with the MOLLE than the ALICE under the approach load. Subsequent tables suggest that the difference between the systems was largely attributable to slow times with the MOLLE on the low crawl obstacle.

Table 11. Time (s) to complete entire obstacle course minus the horizontal pipe and wall, mean (SD).

	Fighting Load	Approach Load
MOLLE	^b 36.74 (4.14)	^a 57.38 (12.99)
ALICE	^b 36.38 (3.43)	^a 51.99 (6.04)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Tables 12 through 15 show the times for individual segments of the obstacle course. The data in Table 12 indicate that, while the volunteers were significantly slower at traversing the low hurdles with the approach load than the fighting load, their speed was not significantly affected by the load-carriage system, although the mean for the MOLLE was about 10% longer than for the ALICE with the approach load.

Table 12. Time (s) to traverse obstacle course hurdles, mean (SD).

	Fighting Load	Approach Load
MOLLE	^b 5.35 (0.53)	^a 7.18 (1.45)
ALICE	^b 5.47 (0.64)	^a 6.50 (0.89)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 13 shows that the volunteers took longer to negotiate the obstacle course zigzag with the approach load than with the fighting load, although the difference was significant only with the MOLLE. There was no significant difference between the load-

carriage systems for the fighting load. However, when carrying the approach load, the volunteers produced a significant 9% longer mean time with the MOLLE than the ALICE.

Table 13. Time (s) to traverse obstacle course zigzag, mean (SD).

	Fighting Load	Approach Load
MOLLE	10.19 ^b (0.94)	11.93 ^a (1.68)
ALICE	10.06 ^b (0.88)	10.96 ^b (0.98)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 14 shows that the volunteers took significantly longer to negotiate the obstacle course low crawl with the approach load than with the fighting load. However there was no significant difference between the load-carriage systems even though, when carrying the approach load, the volunteers averaged 15% longer with the MOLLE than the ALICE. This is likely due to a difference in the pack shape. The ALICE was shorter from top to bottom than the MOLLE. The taller MOLLE had a tendency to press against the back of the soldier's helmet when she dove under the low-crawl obstacle.

Table 14. Time (s) to complete obstacle course low crawl, mean (SD).

	Fighting Load	Approach Load
MOLLE	12.39 ^b (2.58)	27.68 ^a (9.81)
ALICE	12.01 ^b (2.25)	24.17 ^a (4.95)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 15 shows that the volunteers took significantly longer to negotiate the obstacle course 94-foot straight run with the approach load than with the fighting load. However there was no significant difference between the load-carriage systems.

Table 15. Time (s) to complete obstacle course 94-foot straight run, mean (SD).

	Fighting Load	Approach Load
MOLLE	8.82 ^b (0.87)	10.59 ^a (0.92)
ALICE	8.84 ^b (0.68)	10.36 ^a (1.54)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Because of the high failure rate on the horizontal pipe, comparison was based on how far the volunteers got on the pipe rather than how long they took. The 12' long pipe was divided by colored bands into four equally spaced zones. If a volunteer failed to negotiate the entire pipe, the number of zones she completed was recorded. Table 16 shows that, with the fighting load, the volunteers averaged about 3.5 zones, while they only averaged about 2 zones with the approach load, a statistically significant difference only for the MOLLE. However, there was no significant difference between load-carriage systems, even though the volunteers averaged 23% more zones with the ALICE than with the MOLLE. The higher center of mass of the MOLLE likely placed increased weight on the soldiers' hands, making it more difficult to traverse the pipe.

Table 16. Zones achieved when traversing obstacle course horizontal pipe, mean.

	Fighting Load	Approach Load
MOLLE	3.45 ^a	2.00 ^b
ALICE	3.44 ^a	2.45 ^{a,b}

Values superscripted with different letters are significantly ($p < 0.05$) different.

As mentioned previously, the women had a very high failure rate at traversing the 1.37 m high wall (Table 17). With the fighting load, only 55% of the women could get over the wall using both load-carriage systems. With the approach load, only 36% of the women could get over the wall with the ALICE and only 11% could make it over with the MOLLE; a difference between systems that was not statistically significant. Generally, packs with a higher center of mass facilitate wall traversal, because the soldier does not have to lift the load as high to get it over the wall. With its higher center of mass, the MOLLE would have been expected to produce a higher success percentage for wall traversal than the ALICE. There is no apparent reason why the opposite was true.

Wall traversal is clearly a problem for females. In previous experimentation, virtually no males have failed to traverse the wall, although some have had difficulty doing so. This appears to be one battlefield activity, critical for combat effectiveness and survival, at which females are at a decided disadvantage. Their difficulty in traversing the wall is likely attributable to their shorter stature and lower body-center-of-mass, necessitating a higher lift of body-plus-load, and to less upper and lower body strength and power.

Table 17. Percentage of successful attempts to traverse the obstacle course wall.

	Fighting Load	Approach Load
MOLLE	0.546 ^a	0.111 ^b
ALICE	0.556 ^a	0.364 ^{a,b}

Values superscripted with different letters are significantly ($p < 0.05$) different.

WEAPONS SKILLS

It should be noted that for the grenade throw results in Table 18, a lower number for distance from the target center is more desirable. Most of the women had trouble reaching the standard 35 meter distant target with the grenade, accounting for most of their deviation from the target. Hit percentage was not calculated for the females because only two of them could reach the 5-meter diameter target at all. For the no-load, MOLLE fighting, and ALICE fighting conditions, mean distances from the target center were 47 feet, 57 feet, and 56 feet, respectively. This compares to male distances in the 9-12 foot range. The distance from the target was significantly less for the no-load condition than for the fighting loads, which didn't differ significantly from each other. Thus, the fighting load did impede accuracy by about 20%, most likely due to shortening throwing distance. That makes sense in that the fighting vest has to be at least somewhat restrictive. The ALICE appeared to have a small, nonsignificant advantage over the MOLLE. The best throwers seemed to be the volunteers who reported having played softball.

Table 18. 35-meter grenade throw score (inches from target center), mean (SD).

	No Load	MOLLE Fighting Load	ALICE Fighting Load
score	568.96 ^b (258.01)	684.06 ^a (198.47)	666.86 ^a (197.48)

Values superscripted with different letters are significantly ($p < 0.05$) different.

There were no significant differences among the ALICE, MOLLE, and no-load conditions for shooting accuracy as measured by DCM, SGT, and % HITS (Table 19). However, shot groups were significantly tighter in the prone than the standing position. There was also a significant load-carriage condition by shooting position interaction effect for SGT; in the standing position both the ALICE and MOLLE fighting loads produced better scores than the no-load condition, while in the prone position no such advantage was evidenced. Sighting time was significantly shorter for both the MOLLE and ALICE fighting loads than for the no-load condition. In both the prone and standing position, the women sighted faster with both fighting loads than in the no-load condition, without sacrificing accuracy.

Table 19. Shooting scores with no load, and ALICE and MOLLE fighting loads, mean (SD).

PRONE	No load	ALICE	MOLLE
DCM	5.8(2.7)	5.8(1.3)	6.0(2.4)
SGT	38.9(29.9)	45.8(56.3)	39.3(40.5)
% Hits	92.5(23.0)	94.2(17.3)	94.2(11.6)
STIME	8.2(1.7)	7.3(2.1)	7.4(2.6)
STANDING	No load	ALICE	MOLLE
DCM	6.2(1.4)	6.2(2.1)	6.3(2.5)
SGT	96.8(37.6)	72.2(49.5)	70.5(37.6)
% Hits	97.5(8.7)	92.5(10.6)	95.0(6.7)
STIME	11.2(3.3)	9.9(2.1)	9.8(2.2)

Key Abbreviations:

DCM = distance from center of mass (mm).

SGT = shot group tightness (mm²).

% Hits = percentage of targets hit.

STIME = sighting time (sec).

Subjective comments obtained from the 12 volunteers are listed in Tables 20 and 21. Multiple comments were allowed, so the total number of comments could exceed 12. For the ALICE there were 11 positive comments, 11 negative comments, and 3 suggestions for improvement. For the MOLLE there were 6 positive comments, 19 negative comments, and 19 suggestions for improvement. The greater number of suggestions for improvements for the MOLLE is likely to be related to the volunteers' knowledge that they were evaluating a new load-carriage system, planned for general use in the Army. Several of the complaints about and suggestions for improvement to the MOLLE were related to the Interceptor body armor, which was uncomfortable and restrictive for many of the women.

Table 20. Subjective comments about the ALICE.

<u>Positive Comments</u>	<u>Number</u>
The weapon could be easily stabilized in both the standing and prone positions by tucking its butt into the load-carriage system's shoulder strap.	3
The equipment was easy to put on, and is simple.	3
There were no problems while shooting.	2
While shooting in the prone position the system helped stabilize the weapon.	1
It is very comfortable to wear.	1
This system allows your body to stay cooler than the MOLLE	1
<u>Negative Comments</u>	<u>Number</u>
Could not get the butt of the weapon into the shoulder/armpit area in the standing position.	6
It is hard to get a good sight picture when the weapon is stabilized under the shoulder strap.	2
When shooting prone, filled pouches stick into you, making it very uncomfortable to shoot.	2
In the standing position, there was restricted arm movement when trying to lift the arms to shoot properly.	1
<u>Suggested improvements</u>	<u>Number</u>
Provide a shoulder strap pocket in the correct position, or better yet, one that is adjustable to cradle the butt of the rifle when shooting.	1
Adjustments should be made to fit women's bodies.	1
There should be more padding in the arm area.	1

Table 21. Subjective comments about the MOLLE.

<u>Positive Comments</u>	<u>Number</u>
The weapon could be easily stabilized in both the standing and prone positions by tucking its butt into the load-carriage system's shoulder strap.	4
The load feels lighter while marching.	1
It is easier to adjust the position of the vest to get into a comfortable position while shooting prone.	1
<u>Negative Comments</u>	<u>Number</u>
The high body armor collar displaces the helmet when shooting.	6
The body armor restricts movement.	3
Could not get the butt of the weapon into the shoulder/armpit area in the standing position.	3
The system feels heavy.	2
The belt can bruise the pelvis area.	2
The system is hotter to wear	1
When shooting prone, filled pouches stick into you, making it very uncomfortable to shoot.	1
The interior snap attachments dig into your hip when you are shooting prone.	1
<u>Suggested improvements</u>	<u>Number</u>
The collar on the body armor should either be lowered or eliminated.	5
The bulk of the shoulder material should be decreased in the body armor because it restricts range of movement.	4
To facilitate breathing, the body armor should be contoured in the chest area to allow for different women's bust sizes.	3
The interior snap attachments of the body armor that dig into the body should be removed or repositioned.	1
If there is a way to soften the material of the body armor while providing the same ballistic protection it should be done.	1

The body armor should be shortened to allow the belt to fit snugly around the waist and be in the proper position on the back to help carry the load properly.

1

The belt should fit beneath the body armor.

1

The strain on the back should be decreased by putting more of the weight on the hips.

1

An indentation should be put into the material near the armpit area to secure the weapon in the proper position.

1

The pockets should be put in more comfortable positions so when you are laying down things don't dig into you.

1

Table 22 shows which system each volunteer would choose if she had a choice. It appears that, as tested, the ALICE was preferred by more of the female soldiers. However, four of the women felt they would prefer the MOLLE if modifications were made to improve function, safety and comfort, suggesting a preference edge for a modified MOLLE. However, there is no way of knowing if any particular set of modifications would be satisfactory to all of those women.

Table 22. Number of soldiers who would choose each system if given a choice.

ALICE	4
MOLLE	2
MOLLE, if modifications were made to improve function, safety and comfort	4
Either System	1
Neither System	1

COMFORT

The comparison of comfort of the two load-carriage systems, presented in this section, is based on the results of the questionnaires administered to the volunteers after each maximal-speed 2-mile walk/run.

Table 23 shows that, as to frequency of complaints concerning the shoulder, the MOLLE produced 11% fewer complaints than the ALICE for the fighting load, 26% fewer complaints for the approach load, and 22% fewer complaints for the sustainment load, although these differences were not statistically significant. As expected, the number of shoulder complaints increased with the load.

Table 23. Shoulder complaint frequency as a percentage of maximum possible responses*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	24.24%	33.34%	50.00%
ALICE	27.28%	45.00%	63.89%

* These percentages were obtained by totaling the number of subjects' responses that indicated some level of discomfort in the shoulder region and dividing this total by the maximum possible number of responses.

Table 24 shows that, as to the severity of complaints concerning the shoulder, the MOLLE and ALICE didn't differ significantly or notably for the fighting load. With the approach load, the complaint severity was not significantly different, even though the MOLLE elicited a mean 20% lower shoulder complaint severity than the ALICE. With the sustainment load, the MOLLE produced a significant 33% lower shoulder complaint severity than the ALICE.

Table 24. Shoulder pain/discomfort as a percentage of maximum possible score*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	1.20% ^d	2.60% ^{c,d}	4.63% ^b
ALICE	1.39% ^d	3.26% ^{b,c}	6.89% ^a

Values superscripted with different letters are significantly ($p < 0.05$) different.

*These percentages were obtained by taking a weighted score for degree of discomfort for each body area that make up the shoulder region and dividing by the maximum possible score that could have been achieved.

Table 25 shows that, as to frequency of complaints concerning the hips, with the fighting load the MOLLE produced 14% fewer complaints than did the ALICE. Yet with the approach load, the MOLLE produced 6% more hip complaints than the ALICE, and with the sustainment load, 40% more complaints than the ALICE. It is interesting to note that frequency of hip complaints for the MOLLE did not differ at all between the approach and sustainment loads, and for the ALICE, the frequency of complaints was actually lower for the sustainment load than for the approach load.

Table 25. Hip complaint frequency as a percentage of maximum possible responses*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	13.63%	29.17%	29.17%
ALICE	15.91%	27.50%	20.83%

*These percentages were obtained by totaling the number of subjects' responses that indicated some level of discomfort in the hip region and dividing this total by the maximum possible number of responses.

Table 26 shows that, as to the severity of complaints concerning the hips, the MOLLE and ALICE didn't differ significantly, even though the mean severity of discomfort of the MOLLE with the sustainment load was 74% more than with the ALICE. The difference between loads was not significant for either load-carriage system.

Table 26. Hip pain/discomfort as a percentage of maximum possible score*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	1.28% ^{a,b}	2.60% ^{a,b}	3.39% ^a
ALICE	1.14% ^b	2.66% ^{a,b}	1.95% ^{a,b}

Values superscripted with different letters are significantly ($p < 0.05$) different.

*These percentages were obtained by taking a weighted score for degree of discomfort for the body areas that make up the hip region and dividing by the maximum possible score that could have been achieved.

The shoulders and hips are the main contact points of any framed backpack. Table 27 compares the load-carriage systems and loads as to complaint frequencies for all body areas excluding the shoulders and hips; many of these were likely due to indirect effects. It appears that the MOLLE produced more complaints with the fighting load, about the same number with the approach load, and less with the sustainment load than the ALICE.

Table 27. All other body areas complaint frequency as a percentage of maximum possible responses*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	19.49%	14.88%	19.64%
ALICE	12.34%	15.71%	25.59%

* These percentages were obtained by totaling the number of subjects' responses that indicated some level of discomfort in the shoulder region and dividing this total by the maximum possible number of responses.

As to severity of complaints for all body areas excluding the shoulders and hips, Table 28 shows that the only statistically significant effect was that the ALICE sustainment load produced more severity of complaints than any of the other lighter-load conditions with either pack. The overall trend of severity of complaints is similar to that for complaint frequency; the MOLLE produced more severe complaints with the fighting load, similar severity with the approach load, and less severity with the sustainment load than the ALICE.

Table 28. All other body areas pain/discomfort as a percentage of maximum possible score*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.499% ^b	0.351% ^b	0.606% ^{a,b}
ALICE	0.348% ^b	0.421% ^b	0.818% ^a

Values superscripted with different letters are significantly ($p < 0.05$) different.

*These percentages were obtained by taking a weighted score for degree of discomfort for each body area that make up areas other than the hip and shoulder region and dividing by the maximum possible score that could have been achieved.

Table 29 indicates that frequency of total body complaints increased with the load. The MOLLE produced 18% more complaints with the fighting load than the ALICE, 15% fewer complaints with the approach load, and 16% fewer complaints with the sustainment load.

Table 29. Total body complaint frequency as a percentage of maximum possible responses*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	19.7%	21.2%	28.8%
ALICE	16.7%	25.0%	34.4%

* These percentages were obtained by totaling the number of subjects' responses that indicated some level of discomfort throughout the entire body and dividing this total by the maximum possible number of responses.

Table 30 shows an overall trend towards greater severity of total body pain and discomfort as the load increased. In the only statistically significant difference between load-carriage systems, the ALICE produced 29% greater discomfort than the MOLLE for the sustainment load. With the approach load, severity was 19% greater with the ALICE than the MOLLE. However, with the fighting load, the MOLLE produced 18% greater severity of complaints than the ALICE.

Table 30. Total body pain/discomfort as a percentage of maximum possible score*.

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.280% ^{c,d}	0.354% ^{c,d}	0.590% ^b
ALICE	0.237% ^d	0.421% ^c	0.763% ^a

Values superscripted with different letters are significantly ($p < 0.05$) different.

* These percentages were obtained by taking a weighted score for degree of discomfort for the entire body and dividing by the maximum possible score that could have been achieved.

BIOMECHANICS

Stride length (Table 31) averaged about 1.45 m for all test conditions. However, stride length with the MOLLE sustainment load was significantly shorter than with the MOLLE fighting load or ALICE approach load, which produced the longest stride lengths. These differences don't appear to be of practical importance.

Table 31. Stride length (m), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	1.47 ^a (0.086)	1.45 ^{a,b} (0.087)	1.43 ^b (0.078)
ALICE	1.45 ^{a,b} (0.105)	1.47 ^a (0.087)	1.45 ^{a,b} (0.101)

Values superscripted with different letters are significantly ($p < 0.05$) different.

The volunteers stepped slightly slower than 1 stride per second (Table 32). None of the differences between test conditions were significant or of apparent practical value.

Table 32. Stride frequency (strides/s), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.930 ^a (0.057)	0.937 ^a (0.073)	0.947 ^a (0.053)
ALICE	0.948 ^a (0.087)	0.945 ^a (0.060)	0.942 ^a (0.076)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 33 shows that the percentage of stride time in which the volunteers were on both feet (double support) increased significantly with the load. This is a positive adaptation to load carriage; increased double support brings about greater stability and spreads the load over 2 feet for a greater duration. There was no significant difference between the load-carriage systems, although with the approach and sustainment loads, the volunteers were in double support 6%-7% longer with the MOLLE than the ALICE.

Table 33. Double support duration (% of stride time), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	13.5 ^d (2.4)	15.5 ^{b,c} (3.2)	17.3 ^a (3.5)
ALICE	14.0 ^d (3.8)	14.5 ^{c,d} (2.1)	16.3 ^{a,b} (3.0)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Rear knee angle is defined as the sagittal-plane angle formed behind the knee by the upper and lower legs. The minimum rear knee angle indicates the maximum degree of knee bend during the stride. Table 34 shows that there were no significant differences between any of the experimental conditions as to minimum rear knee angle. Yet, an apparent trend towards less knee bend with higher loads suggests that, as the load increases, the foot doesn't swing back as far after it comes off the ground. This is consistent with the increased double support time with increasing loads; if the foot is to spend more time on the ground, it can't be swung back as far after it loses contact with the ground.

Table 34. Minimum rear knee angle (deg), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	107.4 ^{a,b} (5.26)	107.9 ^{a,b} (5.51)	108.6 ^a (6.51)
ALICE	106.7 ^b (5.63)	107.4 ^{a,b} (5.48)	108.0 ^{a,b} (6.89)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Maximum rear knee angle indicates the degree to which the knee is straightened during the stride, generally at the time the foot hits the ground. A greater maximum angle means more straightening. Table 35 indicates that for all test conditions, the women came about 8° short of a fully straightened leg (180°).

Table 35. Maximum rear knee angle (deg), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	172.2 ^a (4.12)	172.1 ^a (4.37)	172.2 ^a (4.34)
ALICE	172.3 ^a (4.46)	172.7 ^a (4.31)	172.1 ^a (4.65)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 36 shows that knee range of motion was not significantly affected by load-carriage system or load. However, there was a trend towards reduced range of motion with increasing load, which serves to enhance stability during load carriage and reduce body joint torque relative to what it would be if a normal unloaded walking stride were maintained.

Table 36. Knee range of motion (deg), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	64.78 ^{a,b} (4.68)	64.28 ^{a,b} (5.87)	63.56 ^b (5.70)
ALICE	65.58 ^a (6.37)	65.35 ^a (5.87)	64.15 ^{a,b} (6.94)

Values superscripted with different letters are significantly ($p < 0.05$) different.

The sagittal plane trunk angle is defined as the sagittal-plane angle formed between the trunk and a vertical line through the hip. The maximum value of that angle is an indicator of the greatest degree to which the trunk is inclined forward during load carriage; a positive angle indicates forward trunk lean and a negative angle rearward trunk lean. A more upright walking posture is considered desirable because it is closer to the normal unloaded walking posture and is usually more efficient. Table 37 shows that even at their most forward-leaning trunk position, the volunteers actually leaned back somewhat with the fighting load, likely due to the weight of both the ammunition on the front of their fighting vests and the rifle carried at "port arms" (held in both hands in front of the body). With the fighting load, there was significantly greater rearward trunk lean with the MOLLE than the ALICE indicating that either more of the load was in front of the body, or that the load in front of the body was positioned lower, or both. With the approach load there was no significant or noteworthy difference between the MOLLE and ALICE. This is likely because the weight on the front and rear of the body balanced each other similarly for the ALICE and MOLLE. Yet with the sustainment load, the trunk inclined forward about 3° more with the ALICE than with the MOLLE, a significant difference. The higher center of mass of the MOLLE pack, as indicated in Table 49, is likely a major factor in trunk inclination. The lower center of mass of the ALICE requires the volunteer to incline the trunk forward more in order to get the center of mass of the pack more directly over the base of support. The significant pack-type by load interaction occurred because of the small effects of pack-type for all but the sustainment load, which showed a large effect.

Table 37. Maximum sagittal plane trunk angle (deg), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	-2.44 ^e (3.68)	5.69 ^c (3.07)	9.46 ^b (3.27)
ALICE	-1.44 ^d (4.60)	5.99 ^c (3.62)	12.26 ^a (3.85)

Values superscripted with different letters are significantly ($p < 0.05$) different.

There is a significant ($p < 0.05$) pack-type by load interaction.

Minimum sagittal plane trunk angle is an indicator of how upright or backwards the trunk becomes during load carriage. Table 38 shows that, with both fighting loads, the volunteers leaned backward 4°-5° at their furthest back-lean position; and the MOLLE produced significant more back-lean than did the ALICE. With the approach load in both systems, the trunk inclined forward 2°-3° at its most upright position, and didn't differ significantly or practically from each other. However, with the sustainment load, the trunk became about 2.5° more upright with the MOLLE than with the ALICE, a significant difference. As the load got heavier, the volunteers became significantly less upright. The reasons for the differences between the ALICE and MOLLE for this variable are the same as those discussed above for the previous variable. In addition to allowing a more desirable upright walking posture, an added advantage of a soldier walking more upright is the increased likelihood of observing potential threats.

Table 38. Minimum sagittal plane trunk angle (deg), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	-5.16 ^e (3.65)	2.52 ^c (2.92)	5.75 ^b (3.25)
ALICE	-4.21 ^d (4.79)	2.42 ^c (3.54)	8.13 ^a (3.55)

Values superscripted with different letters are significantly ($p < 0.05$) different.

There is a significant ($p < 0.05$) pack-type load interaction.

The range of the sagittal plane trunk angle is largely a measure of the front-back sway of the trunk during walking. Table 39 shows that the sway increased significantly as the load increased. The two pack systems differed significantly in sway for both the approach and sustainment loads, for which front-back trunk sway was 11%-13% greater with the ALICE than with the MOLLE. Less sway should be desirable because it represents less perturbation from normal gait and appears less likely to cause fatigue or loss of balance.

Table 39. Sagittal plane trunk angular range (deg), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	2.72 ^d (0.76)	3.17 ^c (0.93)	3.71 ^b (0.98)
ALICE	2.78 ^d (1.09)	3.57 ^b (0.73)	4.13 ^a (1.06)

Values superscripted with different letters are significantly ($p < 0.05$) different. There was a significant ($p < 0.05$) pack-type by load interaction.

The vertical range of the subject's center of mass provides an indication of the degree to which the subject bobs up and down while walking. Table 40 shows that there were no significant load-carriage system effects. There was only one significant effect of load; with the ALICE system, vertical bobbing was greater with the sustainment load than with the fighting load. The small effect appears to be of little practical value.

Table 40. Vertical range (m) of subject center of mass, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.052 ^{a,b} (0.006)	0.051 ^{a,b} (0.005)	0.053 ^{a,b} (0.006)
ALICE	0.051 ^b (0.006)	0.052 ^{a,b} (0.006)	0.054 ^a (0.008)

Values superscripted with different letters are significantly ($p < 0.05$) different. There was a significant ($p < 0.05$) pack-type by load interaction.

Despite little difference in the range of vertical travel of the body center of mass, more effects are evident for center of mass high point (Table 41). Increasing load tended to pull the body down, so that there were significant load effects for both load-carriage systems. The only significant effect of load-carriage system occurred for the approach load, for which the center of mass reached a higher position with the ALICE than with the MOLLE.

Table 41. Maximum body center of mass height (m), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.941 ^a (0.043)	0.930 ^c (0.047)	0.930 ^c (0.042)
ALICE	0.939 ^{a,b} (0.041)	0.937 ^b (0.040)	0.930 ^c (0.044)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 42 shows that the low point of the body's center of mass was affected mainly by the load. Increasing load pulled the body down to a significant degree with both load-carriage systems. Concurrent examination of the maximum and minimum center of mass height data indicates that as the load increased, the center of mass traveled through about the same vertical distance, with the high and low points lowered by about the same amount. As to differences between systems, with the fighting load the body reached a significantly lower point with the ALICE than with the MOLLE. However, with the approach load, the body reached a significantly lower point with the MOLLE than the ALICE. Despite their statistical significance, these inter-system differences do not appear to be of practical importance.

Table 42. Minimum body center of mass height (m), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.890 ^a (0.041)	0.879 ^c (0.045)	0.877 ^{c,d} (0.042)
ALICE	0.888 ^b (0.040)	0.885 ^b (0.038)	0.876 ^d (0.041)

Values superscripted with different letters are significantly ($p < 0.05$) different.

The body accelerates forward when a walker pushes off the foot, and it decelerates when the foot strikes the ground. Thus even while walking at an apparently constant speed, a walker speeds up and slows down with each step. Our volunteers walked at 3 miles per hour for the biomechanical analysis, which translates to about 1.4 m/s. Table 43 shows their minimum speed during walking averaged about 1.2 m/s. For the MOLLE, minimum speed decreased as the load increased, yet for the ALICE this did not occur. Differences between load-carriage systems do not appear notable, despite a significant difference for the approach load.

Table 43. Minimum center of mass horizontal velocity (m/s) mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	1.227 ^{a,b} (0.058)	1.210 ^{b,c} (0.053)	1.188 ^c (0.061)
ALICE	1.216 ^{a,b} (0.072)	1.238 ^a (0.058)	1.212 ^{b,c} (0.058)

Values superscripted with different letters are significantly ($p < 0.05$) different.

The maximum speed reached while walking at an apparent 1.4 m/s was about 1.6 m/s (Table 44). For the MOLLE, maximum speed was reduced when the load exceeded the fighting load, yet for the ALICE, maximum speed was reduced only when the load exceeded the approach load. Differences between load-carriage systems do not appear notable, despite a significant difference for the approach load.

Table 44. Maximum center of mass horizontal velocity (m/s) mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	1.573 ^{a,b} (0.078)	1.541 ^b (0.059)	1.543 ^b (0.070)
ALICE	1.583 ^a (0.095)	1.586 ^a (0.093)	1.558 ^{a,b} (0.099)

Values superscripted with different letters are significantly ($p < 0.05$) different.

It is interesting to observe many significant differences between system/load conditions for peak heel-strike vertical ground reaction force (Table 45). As expected, the heel-strike force increased with the load carried. As to system comparisons, while the load-carriage systems did not differ for the fighting or sustainment loads, the MOLLE produced a significant 3% greater heel-strike force than the ALICE for the approach load. In general, lower impact forces are considered more desirable because they are less potentially injurious.

Table 45. Peak heel strike vertical ground reaction force (N), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	811.6 ^d (84.2)	962.2 ^b (79.3)	1067.9 ^a (94.8)
ALICE	802.9 ^d (82.8)	931.8 ^c (87.6)	1058.5 ^a (84.5)

Values superscripted with different letters are significantly ($p < 0.05$) different.

As seen in Table 46, a similar pattern emerged for the push-off vertical ground reaction force as for the peak heel-strike vertical force. The forces increased significantly with the load carried. While the load-carriage systems did not differ for the fighting or sustainment loads, the MOLLE produced a significant 4% greater vertical push-off force than the ALICE did for the approach load.

Table 46. Peak push-off vertical ground reaction force (N), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	810.3 ^d (75.8)	966.3 ^b (76.7)	1067.3 ^a (79.5)
ALICE	792.2 ^d (78.1)	927.3 ^c (75.2)	1058.3 ^a (69.4)

Values superscripted with different letters are significantly ($p < 0.05$) different.

During walking, the foot normally strikes the ground following the swing phase of the leg, so that the foot exerts a forward force on the ground. In turn, the ground exerts an equal and opposite force on the foot which acts to decelerate the body's forward motion; this is called the braking force. Greater braking force would be expected to be associated with greater fatigue and injury risk. It increases movement and friction between the foot and shoe, which heightens the likelihood of blisters. Table 47 shows that the braking force increased significantly as the load increased, for both load-carriage systems. That is expected, since it takes a greater force to decelerate a greater mass. Yet there were no significant differences between the load-carriage systems as to braking force.

Table 47. Braking force (N) averaged over entire stride, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	22.55 ^a (3.56)	26.91 ^b (3.53)	33.16 ^c (5.88)
ALICE	21.83 ^a (3.58)	25.83 ^b (3.81)	31.97 ^c (5.35)

Values superscripted with different letters are significantly ($p < 0.05$) different.

A similar pattern emerged for peak heel-strike braking force as for braking force averaged over entire stride. Table 48 shows that heel-strike peak braking force increased significantly as the load increased, for both load-carriage systems, with no significant differences between the load-carriage systems.

Table 48. Peak heel strike braking force (N), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	146.85 ^a (19.84)	181.28 ^b (23.82)	215.37 ^c (28.89)
ALICE	139.65 ^a (23.74)	176.68 ^b (29.67)	214.87 ^c (33.46)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Table 49 indicates that for all three loads, the load center of mass was significantly lower for the ALICE than the MOLLE. The higher pack center of mass of the MOLLE helps explain the more upright walking posture it produces, closer to that characteristic of unloaded walking. The difference in center of mass vertical position can be attributed almost completely to the pack-bag shape and location on the frame, since all packs were loaded to place the center of mass at the center of the pack volume. Because the MOLLE pack is relatively tall, adding weight to it significantly raised the center of mass of the total load carried. Because the ALICE pack is lower, adding weight to the pack significantly lowered the load center of mass.

Table 49. Vertical distance (m) from load center of mass to body center of mass, averaged over stride, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.264 ^d (0.047)	0.284 ^c (0.047)	0.374 ^a (0.045)
ALICE	0.237 ^e (0.023)	0.236 ^e (0.015)	0.311 ^b (0.025)

Values superscripted with different letters are significantly ($p < 0.05$) different.

There was a significant ($p < 0.05$) pack-type by load interaction.

Positive distance indicates the pack center of mass is above the body center of mass.

The horizontal distance from load center of mass to body center of mass (Table 50) indicates the position of the load relative to the soldier carrying it. A positive value indicates the load is centered forward of the volunteer's center of mass, while a negative value indicates the load is centered behind the volunteer's center of mass. The more forward the load's center of mass is, the more backward the load carrier tends to lean, while the more rearward the load's center of mass is, the more forward the load carrier tends to lean. These adjustments are made to keep the body-plus-load center of mass over the feet to avoid falling. It can be seen that the center of mass for the fighting load for both systems was 5-7 cm forward of the subject's center of mass, mainly due to the ammunition on the front of the fighting vest. For the approach load, the center of mass for both systems was 9-10 cm *behind* the subject's center of mass, due to the backpack load. For the sustainment load, the load center of mass was 11-15 cm behind the subject's center of mass, due to the backpack load. The sustainment load was the only load showing a significant difference in horizontal center of mass location between load-carriage systems; the center of mass of the ALICE was 4 cm further rearward than the center of mass for the MOLLE. Interestingly, the center of mass of the MOLLE did not move rearward with the increase from approach to sustainment load, despite the overall significance of rearward movement of load center of mass as load increased.

Table 50. Horizontal distance (m) from load center of mass to body center of mass, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.054 ^a (0.049)	-0.101 ^b (0.014)	-0.109 ^b (0.019)
ALICE	0.067 ^a (0.064)	-0.093 ^b (0.015)	-0.151 ^c (0.019)

Values superscripted with different letters are significantly ($p < 0.05$) different.

There is a significant ($p < 0.05$) pack-type by load interaction.

Positive distance indicates the pack center of mass is forward of the body center of mass.

The within-trial standard deviation of the sagittal-plane *horizontal* distance from the pack center of mass to mid-shoulder was used as a measure of the *front-back* pack movement relative to the soldier carrying the pack. Table 51 shows that there was very little of such movement with either pack. Standard deviations were in the range of 1 cm. With the fighting load, there was significantly more movement for the MOLLE than for the ALICE, indicating greater looseness or flexibility of the fighting vest and body armor. The ALICE sustainment load produced the least horizontal movement relative to the soldier.

Table 51. Within-trial standard deviation of sagittal-plane horizontal distance (m) from pack center of mass to mid-shoulder, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.015 ^a (0.012)	0.009 ^{b,c} (0.003)	0.011 ^b (0.007)
ALICE	0.011 ^b (0.005)	0.009 ^b (0.006)	0.006 ^c (0.003)

Values superscripted with different letters are significantly ($p < 0.05$) different.

To measure the *up-down* pack movement relative to the soldier, the within-trial standard deviation of the *vertical* distance from the pack center of mass to mid-shoulder was calculated (Table 52). Vertical movement was in the half-centimeter range. Differences among load-carriage systems and loads were minor.

Table 52. Within-trial standard deviation of vertical distance (m) from pack center of mass to mid-shoulder, mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	0.0069 ^{a,b} (0.007)	0.0052 ^b (0.002)	0.0064 ^{a,b} (0.002)
ALICE	0.0054 ^b (0.003)	0.0063 ^{a,b} (0.003)	0.0059 ^a (0.003)

Values superscripted with different letters are significantly ($p < 0.05$) different.

As seen in Table 53, average pressure under the shoulder straps increased significantly with the load, except for the load increase from the MOLLE approach to sustainment loads. Comparing load-carriage systems, the difference was significant only for the approach load, under which the MOLLE produced 31% higher average pressure than did the ALICE.

Table 53. Average pressure under shoulder straps (psi), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	1.28 ^d (1.03)	2.18 ^a (1.18)	2.02 ^a (1.00)
ALICE	1.42 ^{c,d} (1.60)	1.67 ^{b,c} (0.59)	1.91 ^{a,b} (0.71)

Values superscripted with different letters are significantly ($p < 0.05$) different.

Peak pressure under the shoulder straps (Table 54) showed consistently and significantly increasing pressures with increasing load. The differences between load-carriage systems was similar to that for average pressure, with a significant difference only for the approach load, under which the MOLLE produced 30% higher peak pressure than the ALICE.

Table 54. Peak pressure under shoulder straps (psi), mean (SD).

	Fighting Load	Approach Load	Sustainment Load
MOLLE	2.45 ^c (3.28)	4.44 ^a (3.09)	4.82 ^a (3.30)
ALICE	2.81 ^{b,c} (4.01)	3.42 ^b (1.76)	4.66 ^a (1.96)

Values superscripted with different letters are significantly ($p < 0.05$) different.

DURABILITY OF THE MOLLE

During experimentation on the prototype MOLLE, some of the frames developed vertical cracks near the bottom of the frames where they taper into fittings designed to snap into receptacles on the back of the belts. These cracks may have been caused by torsion on the frame due to trunk rotation during load carriage. It must be noted that the test frames were made using prototype molds, which according to the manufacturer, could have made the frames less durable than if full-production molds had been used. This seems to have been verified via a field trial conducted subsequent to the conclusion of our experiment. In the trial, the MOLLE was tested by the U.S. Army 75th Ranger Regiment; the 1st Battalion of the 24th Infantry, Ft. Lewis, WA; and the 3rd Battalion, 2nd Marines, Camp LeJeune, NC. Testing took place from November 1998 through February 1999. Over 200 MOLLE systems were tested during field operations that included several road marches 10 to 30 miles long with reported weights of 50 to 90 pounds, Airborne Operations, and rough handling such as being thrown onto and off of vehicles while loaded. At the conclusion of the field trial only one damaged frame was reported. Thus properly manufactured MOLLE frames appear durable enough for military use.

DISCUSSION

ENERGY COST

In a previous experiment (9), we observed that pack center of mass location can affect the energy cost of load carriage, with a center of mass high and close to the body associated with a lower energy cost than a center of mass lower and further away from the body. Although the MOLLE pack had a 5-6 cm higher center of mass than the ALICE, the difference was apparently not enough to cause a notable difference in energy cost among the pack systems. In the previous experiment, the center of mass location of the pack was varied in the extreme, using custom apparatus. In the present experiment, the pack represented only part of the total load, with about 40 pounds distributed over other locations on the body. Thus, the center of mass of the pack itself had less impact on the center of mass of the entire load.

TIMED TESTS

The lack of difference between the MOLLE and ALICE as to 2-mile load-carriage speed reflects the lack of difference in energy cost of load carriage between the packs. With the same energy cost, the packs would be expected to yield similar 2-mile run times, because ability to run 2 miles is largely limited by aerobic capacity (7). A similar energy cost should thus yield a similar run time. Load-carriage system did not affect the speed of a short sprint run, which is almost completely anaerobic. Thus the mechanics of running were apparently not differentially affected in an important way by the load-carriage system.

Despite its lack of effect on energy cost of load carriage, the higher center of mass of the MOLLE was apparently enough to affect physical performance. It seemed to account, at least in part, for the slower times for the MOLLE than the ALICE for getting prone and returning to standing; getting prone, rolling three times, and aiming the weapon; and negotiation of the obstacle course, particularly the low crawl and horizontal pipe, as well as the zigzag run and hurdles. The MOLLE made it more difficult to negotiate the low crawl obstacle because its high frame tended to hit against the soldier's helmet as she dove to the ground, pushing the helmet forward over the eyes. The MOLLE's high center of mass was closer to the head and further from the feet. That put more weight on the soldier's arms when she was prone while crawling or trying to get up, or hanging horizontally from a pipe or rope, making body movement more difficult. In addition, the high center of mass gives the body-plus-load a high moment of inertia about the feet. That means that any perturbation of the upper body, as in the zigzag run or hurdles, generates rotational momentum of the upper body which can be difficult to stop, thereby detracting from agility. Because women weigh less than men and have a lower center of mass in proportion to height, given backpack loads change the location of body-plus-load center of mass to a greater degree in women than in men. That can make it more difficult for the women to adjust their normal body movement patterns to compensate for the change. However, an advantage of a higher load center of mass is that less body inclination is needed to keep the center of

mass of body-plus-load over the feet, allowing a more upright walking posture, which is advantageous for observing of potential threats.

The MOLLE proved to have an effective pack-bag quick-release mechanism that allowed the soldier to drop the bag quickly while retaining the fighting load. The ALICE does not have a quick-release mechanism, increasing the time taken to drop the bag. In a previous experiment (4), males were able to throw their arms back and slip out of the ALICE shoulder straps, dropping the pack faster than they could drop the MOLLE pack using the quick-release mechanism. However, the females could not perform that maneuver quickly. The males, most of whom were from combat units, may have practiced the maneuver during their training and combat scenarios. It appeared that several volunteers had difficulty locating the MOLLE quick-release strap tabs, which lie more to the sides than the front of the chest. If the tabs could be more prominently located, time to remove the pack might be considerably reduced.

It seems that women are at a considerable disadvantage relative to men at climbing over walls. Little over half the women could climb over a 54" high wall with the fighting load. With the approach load, only a third of the women could traverse the wall with the ALICE and only one in ten could cross it with the MOLLE. It is not clear why the MOLLE seemed to decrease success at wall traversal. This could put most women at great risk if they found themselves on a battlefield, where many walls and fences could impede forward progress or retreat. In an urban environment, the women would have much difficulty getting into ground-floor windows.

Women also seem to have much more difficulty than men traversing a horizontal pipe, especially with a load. Only a quarter to a third of the women could cross the pipe with the approach load, while in past experiments, a great majority of men could do it, although sometimes with difficulty.

WEAPONS SKILLS

Our previous study on the Land Warrior fighting system (13) showed that human factors issues regarding specific military tasks such as marksmanship must be considered when designing equipment for the soldier. Furthermore, anatomical differences between men and women must be taken into account to ensure that the soldier's health and/or performance is not compromised.

Shooting speed and accuracy were not compromised by either system under the fighting load. Both systems allowed the shooter to engage the target quickly and shoot at it accurately. Rifle shooting in the standing position, under either the ALICE or MOLLE fighting load was significantly better as to shot-group tightness than under no load. It appears likely that the added weight may have damped breathing and body sway movements, two factors that normally detract from shooting accuracy (4, 8). There was no difference between equipment conditions as to accuracy of shooting prone. DCM and % HITS were affected neither by system nor shooting position. The volunteers sighted faster under both fighting loads than when unloaded, without sacrificing accuracy.

Subjective comments indicated that different individuals preferred different load-carriage systems for general use and specifically for shooting. A frequent complaint, especially among the smaller female soldiers, concerned the fit and feel of the body armor. The small armored vests of both systems were too big for the petite female soldier. These problems are more than just an inconvenience; they can impair performance. The bulk of the Interceptor body armor used with the MOLLE restricted movement when the soldier tried to raise her weapon to shoot in the standing position. The collar of the body armor frequently butted up against the helmet making it difficult to raise the head. The Land Warrior produced a similar problem wherein the pack itself butted up against the helmet (13). That problem was worse because the MOLLE collar is more flexible than the Land Warrior pack. Some soldiers were able to make satisfactory adjustments (e.g., folding the collar over) to avoid problems with shooting. However, this study used a simulated 50 m target. At greater distances the interference of the Interceptor body armor might be more telling. Fixing the Interceptor collar design was the most frequently mentioned improvement that could be made to the MOLLE system to help improve shooting performance. The volunteers also stated that the Interceptor body armor should be contoured to accommodate varying bust sizes. Again, this is not only a comfort issue; restricted breathing may cause hyperventilation, which has been shown to impair shooting performance (11).

The prone shooting position was more stable than the standing position, enabling subjects to shoot 48% smaller shot groups while shooting faster. These findings are in keeping with previous studies (12). DCM did not differ between shooting positions, contrary to the findings of the previous studies. The difference might be that our female volunteers were not trained shooters as the infantrymen or Army Rangers were in the three other studies (4, 12, 13). Although these volunteers received practice and training tips prior to actual data collection, mastering the technique of compensating for shots that tend to go to a certain part of the target was difficult to do for these relatively inexperienced shooters. Therefore, the volunteers were instructed to focus on obtaining tight shot groups. The second difference between this study and the previous two studies is that the simulated shooting distance was 50 m in the present study but 100 m in the other studies. Because the target was easier to hit, it may have negated differences between the standing and prone positions for DCM and % HITS.

Women appear to be at a great disadvantage relative to males in regard to the ability to throw a grenade. The women averaged about 50 feet short of the 115 foot (35 m) distant target. Not only would that diminish their ability to harm the enemy on the battlefield, but it could cause shrapnel injury to the thrower. The males missed the center of the target by an average of about 9 feet, but some of these deviations were overthrows or lateral misses. It appears that a typical female soldier caught in a combat situation should not throw grenades in open terrain, but rather to use a grenade launcher if available. Throwing a grenade into a building or bunker or over a wall should be safe for female soldiers. The trend towards shorter grenade throws with the MOLLE can exacerbate women's problem with grenade throwing.

COMFORT

The MOLLE was more comfortable around the shoulder than the ALICE, eliciting fewer and less severe complaints, despite the fact that it produced greater pressures on the shoulder. The MOLLE produced more frequent and severe hip complaints than the ALICE, but frequency and severity of total body complaints were lower for the MOLLE than the ALICE with the approach and sustainment loads. The MOLLE was more uncomfortable than the ALICE under the fighting load, a problem almost completely attributable to the Interceptor body armor; which was extremely uncomfortable for the women. To satisfy women, the Interceptor needs several modifications, including smaller sizes for petite women, and a greater variety of shapes to accommodate the highly variable torso contours of women. Under the approach and sustainment loads, the MOLLE was more comfortable than the ALICE, except in the hip area. However, the MOLLE produced fewer positive comments from the volunteers, more negative comments, and more suggestions for improvement than the ALICE. More volunteers would prefer the ALICE unless changes were made to the MOLLE.

BIOMECHANICS

Lower impact forces of the foot on the ground are generally considered less likely to produce injury, not only of the foot, but of the legs and back. It is not clear why the MOLLE brought about higher heel-strike and push-off forces than the ALICE. In our study on males (4), greater heel-strike forces could be explained by the straighter legs the subjects had when walking with the MOLLE; a straight leg doesn't damp peak force as much as a bent leg. Kinoshita (10) demonstrated an increase in both hip and knee flexion as load increased, a postural change hypothesized to aid in shock absorption. No such trend was observed among our female volunteers, who didn't emulate the male pattern of walking with increasingly bent legs as the load increased. Rather, the females never straightened their legs completely even with the lightest load, and reached a similar degree of knee extension with all loads. While the males came within 2° of full knee extension with all loads, the females were 8° short of full extension for all loads. It's as if females make their adjustment at a light load, then keep that same adjustment even when the load increases further.

Forward trunk flexion has been shown to increase with load (6, 10) as a means of keeping the load-plus-body center of mass over the base of support. The further behind the soldier's back that the pack center of mass is located, the more the soldier must incline the trunk forward to bring the combined center of mass over her feet. In this study, increases in trunk flexion with load were also demonstrated. However, the ALICE produced greater amounts of trunk flexion than did the MOLLE. The higher center of mass of the MOLLE, and its proximity to the back, probably accounts for the difference. The lower and more distant center of mass of the ALICE requires more trunk inclination by the volunteer in order to get the center of mass of the pack over the feet.

A more upright walking posture during load carriage is considered desirable because it is closer to the normal unloaded walking posture and is usually more

efficient. The MOLLE appears to have provided the advantage over the ALICE of maintaining a loaded walking posture closer to a normal unloaded walking posture. The more normal walking posture associated with the MOLLE included a more upright trunk and less front-back trunk sway. The more upright posture with the MOLLE should minimize fatigue over a long hike and allow the soldier to be more observant of potential threats.

The volunteers spent more time in double support with the MOLLE than with the ALICE. This represents a positive adaptation to carrying loads; increased double support brings about greater stability and spreads the load over 2 feet for a greater duration.

Holewijn (5) suggested that skin contact pressures greater than 1.45 psi result in local changes in subcutaneous circulation and recommended that pack contact pressures not exceed this limit in order to avoid skin injury. With both the MOLLE and ALICE, average shoulder strap pressure exceeded this recommended upper limit and peak shoulder strap pressure greatly exceeded it. Pressures for the women were much higher than for the men we previously studied (4). That may be because the pack weight is distributed over a smaller shoulder area for the females than the males. The MOLLE was worse than the ALICE was in regard to pressure on the shoulders, despite fewer complaints by the women of shoulder pain or discomfort. There were no reported shoulder injuries by the females in our study, so Holewijn's recommended limits may be conservative. On the other hand, a very high proportion of the women had shoulder complaints, which were more frequent and severe than complaints about any other part of the body. And our load-carriage trials were only 2-miles long, taking less than 40 minutes. If the women carried loads using either system for several hours, injuries related to pressure on the shoulders might occur.

The MOLLE represents an improvement over the ALICE, mainly for its modularity which gives it great flexibility regarding load configuration. In addition, its quick release mechanism is effective for dropping the pack quickly in an emergency battlefield situation. Cracking of the MOLLE's polymer frame after repeated heavy use was a cause for concern. However, extensive field testing conducted subsequent to the conclusion of the experiment described herein suggests that the problem has been solved via the implementation of full-production casting methods.

CONCLUSIONS

Evidence favoring neither load-carriage system over the other one

- The MOLLE and ALICE did not differ as to energy cost of load carriage.
- The MOLLE and ALICE did not differ as to the speed at which loads could be carried over 2 miles.
- The MOLLE and ALICE did not differ as to the speed at which a soldier could sprint 28.5 m.
- The MOLLE and ALICE did not differ as to knee range of motion.
- The MOLLE and ALICE did not differ as to heel-strike braking force.
- The MOLLE and ALICE did not differ as to the time taken to sight the target and fire with an M16A1.
- Both the MOLLE and the ALICE should be improved to reduce strap pressure on the shoulders.
- The problem of lack of durability of the MOLLE frame appears to have been adequately addressed via the implementation of full-production casting methods.

Factors favoring the ALICE over the MOLLE

- The MOLLE showed a non-significant trend to produce slower times than the ALICE for walking soldiers to get prone and return to standing.
- The MOLLE showed a non-significant trend to produce slower times than the ALICE for walking soldiers to get prone, roll laterally three times, and aim their weapons.
- The MOLLE showed a non-significant trend to produce slower times than the ALICE for volunteers to negotiate an obstacle course. This appears largely attributable to slow times with the MOLLE on the low-crawl obstacle, which may be related to a tendency for the top of the MOLLE pack to hit the soldier in the back of the helmet. Subsequent to the conclusion of the experiment, this problem was addressed by reducing the length of the MOLLE frame.
- The MOLLE showed a non-significant trend to produce slower times than the ALICE for soldiers to negotiate a low hurdle obstacle with the approach load.
- The MOLLE was significantly slower than the ALICE for the speed at which a zigzag obstacle could be negotiated with the approach load.
- The MOLLE showed a non-significant trend to produce slower times than the ALICE for soldiers negotiating a low crawl obstacle with the approach load.
- The MOLLE showed a non-significant trend to make negotiation of a horizontal pipe obstacle under the approach load more difficult than with the ALICE. This may be due to a center of mass of the MOLLE closer to the head, which places more weight on the arms and hands.
- The MOLLE showed a non-significant trend to make negotiation of a 1.37 m high wall obstacle under the approach load more difficult than with the ALICE. The MOLLE's higher center of mass didn't make for greater success in crossing the wall obstacle, as might have been expected.
- The MOLLE had a significantly higher center of mass than the ALICE under all three experimental loads, which may have impaired performance on the low-crawl

because of contact between the pack and helmet, and on the horizontal pipe because of increased weight on the arms when the body is horizontal.

- The MOLLE showed a non-significant trend to produce shorter grenade throws than the ALICE.
- The MOLLE produced fewer positive comments from the volunteers, more negative comments, and more suggestions for improvement than the ALICE. More volunteers would prefer the ALICE unless changes were made to the MOLLE.
- The MOLLE produced more hip complaints and a non-significant trend towards more severe hip complaints than the ALICE under the sustainment load.
- The MOLLE produced more complaints about all body areas other than the shoulders and hips than the ALICE under the fighting load, although fewer such complaints under the sustainment load.
- The MOLLE produced more severe complaints about all body areas other than the shoulders and hips than the ALICE under the fighting load, although less severe such complaints under the sustainment load.
- The MOLLE produced more total-body complaints than the ALICE under the fighting load, but fewer such complaints under the approach and sustainment loads.
- The MOLLE showed a non-significant trend to produce more severe total-body complaints than the ALICE under the fighting load, but less severe such complaints under the approach load, and significantly less severe such complaints under the sustainment load.
- The MOLLE produced greater heel-strike forces than the ALICE, a difference which was significant for the approach load.
- The MOLLE produced greater push-off forces than the ALICE, a difference which was significant for the approach load.
- The MOLLE produced significantly more front-back pack movement relative to the soldier than the ALICE for both the fighting and sustainment loads. However, with both load-carriage systems, horizontal movement between the pack and soldier's body was only in the 1 cm range, indicating good stability.
- The MOLLE produced significantly higher peak and average pressure under the shoulder straps than the ALICE, under the approach load.

Factors favoring the MOLLE over the ALICE

- The MOLLE had a significantly higher center of mass than the ALICE under all three experimental loads, which allows a more upright walking gait, advantageous for observing potential threats.
- The MOLLE's quick-release mechanism functioned well, making it faster than the ALICE (with no quick release mechanism) for jettisoning the pack and getting prone. However, the MOLLE's quick-release system could be improved to make it easier for the soldier to find and reach.
- The MOLLE showed a non-significant trend to produce tighter shot groups in the marksmanship test than the ALICE, particularly for soldiers firing in the prone position.
- The MOLLE showed a non-significant trend to produce fewer shoulder complaints than the ALICE.
- The MOLLE elicited significantly less severe shoulder complaints than the ALICE.

- The MOLLE produced fewer complaints about all body areas other than the shoulders and hips under the sustainment load, although more complaints than the ALICE under the fighting load.
- The MOLLE produced less severe complaints about all body areas other than the shoulders and hips than the ALICE under the sustainment load, although more severe such complaints under the fighting load.
- The MOLLE produced fewer total-body complaints than the ALICE under the approach and sustainment loads, but more such complaints under the fighting load.
- The MOLLE showed a non-significant trend to produce less severe total-body complaints than the ALICE under the approach load, and significantly less severe such complaints under the sustainment load, although more severe such complaints under the fighting load.
- The MOLLE showed a non-significant trend toward more time in double-support than the ALICE under the approach and sustainment loads.
- The MOLLE produced significantly less forward trunk inclination under the sustainment load than the ALICE. The soldiers walked more upright with the MOLLE. This is considered desirable for minimizing fatigue and allowing greater attentiveness to the soldier's surroundings.
- The MOLLE produced significantly less front-back trunk sway than the ALICE under the sustainment load.
- The MOLLE's center of mass was significantly closer horizontally to the soldier's center of mass than was the ALICE's, under the sustainment load. This reduces the amount of forward trunk inclination during walking.

RECOMMENDATIONS

The MOLLE represents an improvement over the ALICE, mainly for its modularity which gives it great flexibility regarding load configuration. In addition, its quick release mechanism is effective for dropping the pack quickly in an emergency battlefield situation. The MOLLE was associated with a more upright walking posture, likely to minimize fatigue over a long hike and allowing the soldier to be more vigilant in regard to potential threats. Additionally, pockets on the MOLLE fighting vest made it easy to secure items and remove them when needed. The pack was relatively comfortable and produced fewer overall complaints about pain and discomfort than the ALICE, potentially leaving soldiers more ready to fight after prolonged foot travel. Although all of the MOLLE/Interceptor configurations were not tested, the modularity of the system offers numerous ways to reduce the load upon contact with the enemy. Thus, the MOLLE seems worthy of replacing the ALICE. However, the MOLLE should be considered a work in progress, in need of continued improvements. Its greatest drawback seems to be its negative effect on agility, as in obstacle course traversal and dodging for cover. The soldiers had fewer positive and more negative comments about the MOLLE than the ALICE, which may be in part attributable to greater familiarity with the ALICE and knowledge that the MOLLE was a prototype under evaluation.

Some recommendations for improving the MOLLE are:

- The pack straps probably should be widened or more fully padded to distribute the load over a greater skin area, because the MOLLE produced higher average and peak pressure under the pack straps than the ALICE, even though reports of discomfort weren't greater. The pressures were above recommended limits.
- The quick-release tabs should be made more easily accessible so that the soldier doesn't have to fumble for them.
- A reduced pack height and front-back dimension would make the MOLLE more effective for crawling under obstacles. The reduced pack height would also make it easier to traverse the horizontal pipe, because less weight would be on the hands. The reduction in pack volume that would result from reducing both pack height and front-back depth could be made up by making the pack wider. While the pack center of mass would become lower, it should not be enough to negatively impact energy cost or physical performance. A lowered center of mass for the MOLLE might also serve to reduce the higher heel-strike forces it was associated with.
- A future system design that allows the pack-bag to be moved up or down on the frame while the soldier is on the move might be considered. At least one commercial pack exists that does that. It would provide the advantage of allowing the pack center of mass to be high when the soldier is walking on relatively flat, smooth territory with little danger of attack. That would provide the benefit of a more normal upright walking gait. The pack could be lowered for walking on more uneven terrain or where evasive maneuvers might be necessary, because the lower pack center of mass provides stability and increases agility.
- As for male soldiers, the MOLLE fighting vest is excessively loose around the waist for most female soldiers, causing undue movement, and should probably be redesigned to fit the waist more snugly.
- The Interceptor body armor designed to work with the MOLLE does not fit the body snugly enough around the waist, making it difficult to fit the pack properly. With the armor and fighting vest in place, the pack waist-belt cannot be cinched down tightly enough to distribute much of the load to the hips. A major design change may be considered, in which the pack belt itself is armored with Kevlar and the vest is shorter so that it doesn't have to be under the pack belt. That would allow the waist-belt to be snugly cinched so that a good portion of the load could be supported on the hips rather than on the shoulders. At the very least, the waist of the armor should be reduced by several inches.
- The fit of the Interceptor body armor is a major problem for women, generating many complaints. A variety of sizes and shapes of body armor are needed to accommodate petite women and women of a wide variety of torso shapes. Several of the women complained that the Interceptor body armor was uncomfortable because it did not accommodate their breasts. Its collar, which was generally uncomfortable, often hit the helmet during prone shooting.

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APPENDIX A

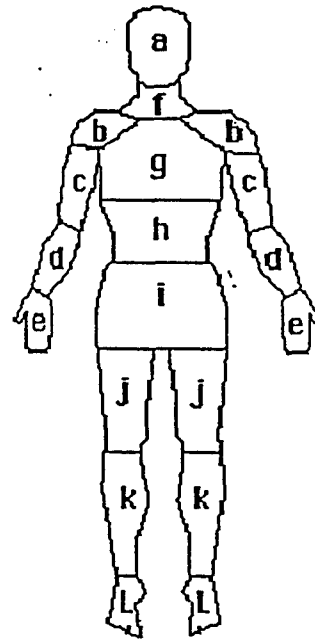
Physical Discomfort Questionnaire

Subject #: _____ Date: _____ Test Condition: _____

INSTRUCTIONS: Rate the degree of SORENESS, PAIN, or DISCOMFORT that you are currently feeling for Body Parts A through L. Do so for the FRONT and the BACK of the body.

FRONT of Body

	a	b	c	d	e	f	g	h	i	j	k	L
NONE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SLIGHT	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
MODERATE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SEVERE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
EXTREME	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐



BACK of Body

	a	b	c	d	e	f	g	h	i	j	k	L
NONE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SLIGHT	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
MODERATE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SEVERE	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
EXTREME	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

