MILITARY MEDICINE, 169, 11:914, 2004

Women's Load Carriage Performance Using Modular Lightweight Load-Carrying Equipment

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The purposes of this study were to evaluate how Modular Lightweight Load-Carrying Equipment (MOLLE) fits women while walking on level surfaces with different loads, to examine women's load carriage performance before and after a simulated march using five load levels, and to examine the relationship between shoulder and leg muscle strength and load carriage performance of women while carrying loads using MOLLE. Seven physically active women carried five levels of load (no load, 20, 30, 40, and 50 pounds) using MOLLE. With increased loads, women showed increased double-limb support time, decreased single-limb support time, increased trunk forward inclination excursion, decreased knee excursion, decreased medial-lateral excursion of center of gravity (COG), and increased vertical excursion of COG. Hip abductor strength was a strong predictor of COG vertical excursion. Some women required modification of the padded hip belt to ensure weight distributed evenly around the pelvis.

Introduction

The percentage of women in the United States Armed Forces increases each year. Since the lifting of the combat exclusion rule in 1993, many military positions were open to women. According to the 2003 U.S. Census Bureau, more than 210,000 women serve on active duty, representing 15% of all active duty personnel in the U. S. Armed Services.[1] However, women are injured at a much higher rate than men during basic combat training. After studying more than 4,000 recruits, Macleod et al.[2] found that 10.9% of female recruits sustained stress fractures, shin splints, and covert fractures as compared with less than 3% of male recruits. Knapik et al.[3] report that women have over twice the injury rate of men during basic combat training. The literature indicates that a number of factors contribute to this higher incidence of injury observed among female recruits during basic training, including lack of upper body strength[4–6] and poorly fitting equipment attributable to a general design based on men's physical characteristics.[7] For example, combat boots are designed for the larger male midfoot and heel dimensions and therefore do not fit female soldiers well and leads to a high incidence of ankle and foot injuries among female recruits during basic training.[7] Similar principles have been applied to the design of personal load-carrying equipment.

In 1999, the U.S. Marine Corps adopted the Modular Lightweight Load-Carrying Equipment (MOLLE) system as standard equipment for the individual Marine. After additional testing, the U.S. Army adopted the modified MOLLE in 2001. MOLLE is a backpack system to replace the All-Purpose Lightweight Individual Carrying Equipment (ALICE) system that had been introduced in 1973. ALICE is an external frame backpack and is carried by the soldier using two shoulder straps. There is a small padded waist belt on ALICE that provides stability but does not transfer load to the hips well. Soldiers often report shoulder discomfort while carrying heavy loads with ALICE.[8] MOLLE consists of two main components: a weight-bearing vest and a modular backpack. The weight-bearing vest has removable pockets to accommodate different mission needs. The modular backpack has an external molded frame, adjustable padded shoulder straps, a padded hip belt, a main rucksack, multiple removable pouches, and a sleeping bag compartment. MOLLE is quite versatile and can be configured in several ways to accommodate the needs of soldiers for specific missions. The advantage of MOLLE over ALICE is that the anatomically contoured external frame and heavily padded hip belt allow the soldier to shift the load from shoulders to hips to lessen shoulder discomfort and to facilitate more upright posture to prevent low back problems.[9,10] In fact, according to LaFiandra et al.,[11] male soldiers could shift 30% of carried weight from shoulders to hips (pelvis) and legs with MOLLE. In addition, male soldiers were able to maintain an upright posture and reported less shoulder and overall discomfort while carrying heavy loads with MOLLE,[9] allowing for improved mobility and a decrease in the incidence of injury.[12]

A number of studies were conducted to examine men's load carriage performance using framed backpacks. When walking with increased loads over level surfaces, men showed consistent changes in gait, including increased trunk forward flexion (inclination),[11,13] decreased stride length,[11] increased stride frequency,[8,11] increased double-limb support time,[8] increased knee flexion,[8,14] and a lower body center of gravity (COG) location.[8] In addition, when walking on a treadmill with increased loads, men showed less trunk rotation while maintaining constant vertical excursion of the COG when compared to men walking on a treadmill without a load.[15,16] These observed changes in gait may adversely affect a soldier's ability to fight by causing low back injuries, foot blister, foot pain, knee pain, stress fractures, and rucksack palsy.[17]

There are very few studies on women's load carriage performance. Researchers have shown that because of lower upper body and torso absolute strength, women experience greater difficulty and typically do not perform as well as men when carrying heavy loads.[18] Women prefer to carry heavy loads on their hips to be as close to their COG as possible[19] as opposed

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This manuscript was received for review in August 2003. The revised manuscript was accepted for publication in December 2003.

to men who prefer to carry the load high on the back.[20] Harman et al.[9,10] examined load carriage performance among active duty male and female soldiers and reported that female soldiers experienced a higher incidence of discomfort than male soldiers when carrying heavy loads, with the highest percentage reporting discomfort in their shoulders. With MOLLE's ability to shift load from the shoulders to the hips, women can carry heavy loads using their strong leg muscles, thus experiencing less discomfort and demonstrating less gait changes. Unfortunately, MOLLE was designed based on male physical characteristics. For example, with a wider pelvis, the padded hip belt of MOLLE may not fit women properly around the waist and therefore may not transfer sufficient weight from shoulders to hips. Harman et al.[10] observed excessive up/down movements of load when the padded hip belt was not clinched tightly around the pelvis of female soldiers, causing hip/pelvis discomfort. On the other hand, if MOLLE shifts the load to women's hips to allow women to use their leg muscles, women's load-carrying performance should be relatively constant with different load levels. Thus, there is a need to further examine female load carriage performance using MOLLE. We postulate that women will show similar biomechanical changes in load carriage performance to men when properly fitted with a load carriage system.

The purposes of this study were to evaluate how MOLLE fits physically active women while walking on level surfaces with different loads, to examine physically active women's load carriage performance before and after a simulated march using five load levels, and to examine the relationship between shoulder and leg muscle strength and load carriage performance of physically active women while carrying loads using MOLLE.

Methods

Subjects

The study was approved by the New York University Committee on Activities Involving Human Subjects. The study was conducted at the Department of Physical Therapy, New York University. Subjects were seven female volunteers who met the following inclusion criteria: between 18 and 30 years of age, no history of leg or back problems, between 153 and 172 cm (5 feet 1 inch to 5 feet 9 inches) in height, between 47 and 68 kg (103–150 pounds) in weight, generally healthy, and regularly exercise. Their mean age was 24.5 (±3.4) years; mean height was 163.9 (±5.4) cm; mean weight was 55.7 (±6.2) kg.

Procedures

Each subject was required to participate in six sessions. Five sessions were for load carriage performance using five load levels including no load, 20, 30, 40, and 50 pounds. One session was for muscle strength measurement. After a brief overview of the study, each subject signed the informed consent. We conducted a quick screening to ensure that each subject was free of back and leg problems and then measured each subject's weight, height, and leg length.

In the load carriage session, a Holter heart rate monitor was strapped around the subject's chest. Twenty 30-mm spherical reflective markers were placed on the subject's body including forehead, chin, and bilaterally on the lateral acromion process, the lateral elbow joint, the lateral radial styloid process, the mid-dorsum of the hand, the greater trochanter, the lateral femoral epicondyle, the lateral malleolus, the head of the fifth metatarsal bone, and the heel. In the no-load condition, subjects did not wear the vest and backpack. In the four loaded conditions, the vest and the backpack were placed on the subject. A foam block with a lead weight placed in its center was used to change the load level and to maintain a constant location of center of mass for the load. The foam block was placed in the main rucksack of the backpack. Subjects wore the same clothes and running shoes for all testing sessions. Each subject's gait pattern on level surface was examined by walking along a 40-foot walkway. In the middle of the walkway was the GAITRite System (CIR Systems, Inc., Clifton, New Jersey) used to capture each subject's spatial and temporal gait parameters. The GAITRite System is an electronic walkway with a pressure-sensitive mat that connects to a personal computer. The five-camera Qualisys MacReflex Motion Analysis System (Model 170, Innovision Systems, Inc., Columbiaville, Michigan) was used to capture the 20 markers placed on the subject. Each subject was instructed to walk at 4.827 (±10%) km/hour to ensure that changes of COG excursion were not caused by variation in walking velocity. We recorded three trials from each subject in each load condition. A simulated march was then conducted on a treadmill (Trackmaster model 500-E AC, JAS Manufacturing, Carrolton, Texas). The simulated march included a 2-minute warm-up and a 2-minute cool-down period and 56 minutes of walking at 4.827 km/hour. During the treadmill walk, the subjects' heart rate, perceived rate of exertion, and discomfort level were recorded at baseline, 10, 20, 30, 40, 50, and 58 minutes. The discomfort level was measured using the visual analog scale (from 0 to 100 mm).[21] The perceived rate of exertion was measured by the modified Borg scale, ranging from 1 to 10.[22] We monitored the subjects' heart rate for safety reasons. The session ended if the subject reached 80% of their age-expected maximum heart rate (80% of 220-age). The subjects were allowed to adjust their shoulder straps and tighten their hip belt during the treadmill walk to mimic such activities that would normally occur during military marches. After each subject completed the simulated march, the subject repeated the gait analysis.

During the muscle strength measurement session, we assessed the strength of two muscle groups around each knee (flexors and extensors), four muscle groups around each hip (flexors, extensors, abductors, and adductors), and six muscle groups around each shoulder (flexors, extensors, abductors, adductors, horizontal abductors, and horizontal adductors). Muscle strength was measured using the Biodex II isokinetic dynamometer in the isokinetic mode and in the position suggested by the manufacturer (Biodex Medical System, Inc., Shirley, New York). After a warm-up period, each subject performed three isokinetic contractions at 90 degrees/second.

Outcomes

Self-reported discomfort level during the simulated march indicates how MOLLE fits each subject at five load levels. Each subject's load carriage performance before and after a simulated march was examined by: spatial-temporal parameters of gait (cadence, stride length, single-limb support time, double-limb support time, and base of support); head, trunk, hip, knee, and ankle joint excursion in the sagittal plane; and medial-lateral and vertical excursions of COG. MacReflex software calculated joint excursions in the sagittal plane. The coordinates of the 20 markers were exported to a custom-written program to calculate medial-lateral and vertical COG excursions based on the formula developed by Hatze.[23] Muscle strength was determined as the total area under the force curve for three isokinetic contractions at 90 degrees/second for each muscle group.

Data Analysis

Data were analyzed by SPSS for Windows (versions 11.0). The researchers first examined whether there were significant differences between pre- and post-treadmill trials for each variable using one-way analysis of variance. If there were no significant differences, pre- and post-treadmill data were combined for analysis of variance with repeated measures to examine the effect of load levels (five levels) on discomfort, spatial-temporal gait parameters, joint excursions, and COG excursions. If the load level had a significant effect on a specific variable, post hoc analyses, using Bonferroni correction to adjust the significance level to 0.005, were conducted. Stepwise multiple regression analysis was used to examine the ability of shoulder, hip, and knee muscle strength to predict COG excursions for different loads.

Results

Women's Load Carriage Performance

Six of seven subjects successfully completed all six sessions. Three subjects had special pads made to ensure weight was distributed evenly around the pelvis. One of these three subjects stopped after 34 minutes during the treadmill walk with 40 pounds due to significant discomfort over the iliac crests and anterior superior iliac spines. This subject did not participate in the 50-pound session. Table I shows descriptive data on discomfort. Discomfort increased as the load increased ($p < 0.05$). Post hoc analyses did not reveal differences between any two conditions with significance level set at 0.005. All subjects reported discomfort over the anterior superior iliac spines, iliac crests, the back of the neck, and the interscapular area during the 40- and 50-pound sessions.

We did not find significant difference between pre- and post-treadmill data on spatial-temporal gait parameters, joint excursion data, and COG excursions. Therefore, the mean of pre- and post-treadmill data were used to examine the effect of load levels on gait. Table II shows the mean and SD of spatial and temporal gait parameters at five load levels. Double-limb support time became longer as the load increased ($p < 0.0001$). Post hoc analyses showed that the no-load condition was different from the 40-pound condition ($p < 0.03$) and the 20-pound condition was different from the 50-pound condition ($p < 0.02$). In contrast, single-limb support time became shorter as the load increased ($p < 0.001$). Post hoc analyses did not reveal differences between any two conditions with significance level set at 0.005.

TABLE I

DISCOMFORT LEVEL AT FIVE LOAD LEVELS

Load Level	Mean (mm)	SD (mm)
No load	1.2	1.5
20 pound	11.0	12.3
30 pound	22.3	21.8
40 pound	28.0	27.2
50 pound	30.7	28.5

Table III shows the mean and SD of joint excursion data at five load levels. Hip joint excursion became larger as the load increased ($p < 0.0{,}001$). Post hoc analyses revealed that hip joint excursion at the no-load condition was less than that of the 30-pound ($p < 0.006$), 40-pound ($p < 0.001$), and 50-pound conditions ($p < 0.001$). Hip joint excursion at the 20-pound condition was also less than that of the 40-pound ($p < 0.004$) and 50-pound conditions ($p < 0.01$). Knee joint excursion became smaller as the load increased ($p < 0.005$). Post hoc analyses revealed that knee joint excursion at the no-load condition was less than that at the 30-pound ($p < 0.03$) and 50-pound conditions ($p < 0.05$). Head and ankle excursions remained relatively similar in all five conditions.

Table IV shows the mean and SD of medial-lateral and vertical COG excursions at five load levels. Medial-lateral COG excursion decreased as the load increased ($p < 0.004$). Post hoc analyses did not reveal differences between any two conditions with significance level set at 0.005. Vertical COG excursion increased with increased load ($p < 0.002$). Post hoc analyses showed that vertical COG excursion at the no-load condition was smaller when compared with the 20-pound condition ($p < 0.009$).

Muscle Strength and Women's Load Carriage Performance

We conducted stepwise multiple regression analysis on muscle strength with COG excursion at each load level. At the no-load condition, shoulder horizontal adductors, hip adductors, shoulder flexors, knee extensors and flexors, and hip flexors strongly predicted medial-lateral COG excursion ($r^2 = 1$, $p < 0.04$). Hip abductors strongly predicted vertical COG excursion at the 20-pound ($r^2 = 0.659$, $p < 0.03$) and 30-pound ($r^2 = 0.707$, $p < 0.02$) conditions.

Discussion

MOLLE Fits Women

Based on the data regarding self-reported discomfort level and load carriage performance, MOLLE fits our female subjects relatively well. The straight, padded hip belt was modified with custom-made pads to lessen excessive pressure on the bony prominence of the pelvis for three (43%) of seven subjects. After the modification, all except one subject was able to complete tasks required in this study; none of the six remaining subjects reported severe discomfort over the pelvic area. The padded hip belt was quite snug on the subject, preventing up and down movements between the backpack system and the subject's pelvis. The one subject that dropped out of the study had the greatest difference between the waist and hip circumference (the widest pelvis) of the seven subjects. Even with pads, she still reported excessive discomfort over her anterior superior iliac spines and was unable to complete the 40-pound trial and did not participate in the 50-pound trial. For those women with

TABLE II

SPATIAL AND TEMPORAL GAIT PARAMETERS AT FIVE LOAD LEVELS

Load Level	Cadence (times/min) Mean (SD)	Stride Length (cm)	Double-Limb Support Time (% of Stride Time)	Single-Limb Support Time (% of Stride Time)	Base of Support (cm)
No load	116.29 (3.66)	141.11 (2.56)	24.96 (2.27)	37.67 (1.76)	9.46 (1.21)
20 pound	117.99 (4.50)	138.10 (3.93)	26.95 (1.30)	36.30 (1.53)	8.94 (1.36)
30 pound	117.65 (2.10)	138.50 (4.72)	27.47 (1.57)	36.48 (0.88)	8.89 (1.46)
40 pound	117.53 (3.73)	139.18 (6.18)	28.7 (1.35)	36.06 (0.80)	8.98 (1.82)
50 pound	117.89 (6.17)	137.66 (5.97)	29.1 (0.80)	35.20 (0.78)	9.11 (1.77)

TABLE III

JOINT EXCURSIONS AT FIVE LOAD LEVELS

Load Level/ Excursion	Head (degrees) Mean (SD)	Hip (degrees)	Knee (degrees)	Ankle (degrees)
No load	4.83 (1.39)	21.05 (4.39)	63.81 (4.05)	35.77 (3.44)
20 pound	5.77 (3.06)	28.22 (5.11)	62.46 (4.42)	37.65 (1.79)
30 pound	7.16 (4.66)	31.25 (6.17)	60.20 (4.23)	38.96 (1.59)
40 pound	6.57 (3.33)	35.38 (4.94)	59.54 (2.19)	39.54 (1.65)
50 pound	6.89 (3.05)	36.74 (3.93)	58.97 (2.54)	38.09 (5.33)

TABLE IV

COG EXCURSION AT FIVE LOAD LEVELS

Load Level/COG Excursion	Medial-Lateral COG Excursion (mm) Mean (SD)	Vertical COG Excursion (mm)
No load	31.18 (5.98)	35.17 (6.34)
20 pound	26.44 (6.68)	41.12 (8.04)
30 pound	22.54 (5.12)	40.43 (9.51)
40 pound	24.37 (5.91)	41.55 (11.9)
50 pound	24.06 (2.43)	38.18 (9.02)

small waists and wide pelvises, hip belt adjustments may be needed; as observed in this study, with minor modification using pads shaped according to the pelvis, sufficient load was shifted from shoulders to hips. Our subjects did not report shoulder discomfort, a fact making our findings different from previous load carriage studies on MOLLE. For instance, Harman et al.[9,10] reported that both male and female soldiers had discomfort over their shoulders while carrying loads with MOLLE. Harman et al.[9,10] did not modify the hip belt of a prototype MOLLE and stated that the hip belt did not cinch tightly around the waist to shift weight from shoulders to hips, thus resulting in shoulder discomfort. As our findings show, a properly fit hip belt seems essential for minimizing shoulder and pelvis (hip) discomfort.

Women's Load Carriage Performance Using MOLLE

In general, women in this study demonstrated load carriage performance similar to that of men using MOLLE. Based on spatial and temporal gait data, our subjects increased the double-limb support time and decreased single-limb support time with increased loads. Our finding are similar to those reported by Harman et al.[8] However, in contrast to the literature,[8,11,12] our subjects did not increase their cadence or decrease their stride length as the load increased. In fact, the data of this study actually showed trends consistent with previous load carriage performance studies but due to a very conservative significance level (0.005) failed to show differences among load conditions.

In this study, women leaned their trunks forward to maintain the combined load and body COG over the base of support while carrying a load with MOLLE. This finding is similar to those reported by LaFiandra et al.[11] and Goh et al.[13] on men's load carriage performance on the treadmill and on level surface. Different from men, we observed that women hyperextended their neck and brought both shoulders forward (shoulder protraction) to maintain the upright trunk posture while carrying a load using MOLLE. This change in standing posture may be the reason that women experienced discomfort and soreness over the back of the neck and the interscapular area. We suspect that women adopt a neck hyperextension and shoulder protraction posture to compensate for weak upper body muscle strength. LaFiandra et al.[16] reported that men decreased arm swings while walking with a loaded backpack. Similarly, we observed decreased arm swings among women in this study, which may also contribute to soreness over the interscapular area. Neck and upper back discomfort during women's load carriage performance found in this study has not been reported previously. Our finding also showed that women exhibited decreased knee excursion as the load increased. Findings of this study are consistent with those reported by previous researchers on men's load carriage performance[8,14] and on women's load carriage performance.[10] Holt et al.[15] found that men stiffen their lower extremities by decreasing knee excursion to carry heavy loads. We speculate that, with MOLLE shifting the load from shoulders to the pelvis and hips, female subjects in this study were also able to carry heavy loads by decreasing knee excursion to stiffen their legs.

Although carrying increased loads, our female subjects adopted the strategy of decreasing medial-lateral COG excursion and increasing vertical COG displacement. Previous studies of both women and men did not examine medial-lateral displacement of COG in load carriage performance. Restricting

COG excursion is a strategy to limit the metabolic cost of walking.[15] We suspect that women decreased medial-lateral COG excursion to limit the metabolic cost of carrying a load using MOLLE. Vertical COG displacement provides an indication of the up and down movements of the whole body and the load during walking. Our finding differs from the load carriage studies by Holt et al.[15] on men and Harman et al.[10] on women, both of which showed that COG vertical excursions remained essentially the same with increased loads. Holt et al.[15] examined men's load carriage performance using a backpack without waist belt. Harman et al.[10] examined women's load carriage performance using a prototype MOLLE which did not allow the hip belt to cinch tightly around the waist. We suspect that without a tight waist belt shifting weight from shoulders to hips, men and women restrain up and down movements of the body against the backpack to prevent the backpack from rubbing against bony prominence around the pelvis. In this study, the hip belt was tightened around each subject's waist and did not allow up and down movement of the backpack against the body. Therefore, our female subjects were able to use a different load-carrying strategy to move the body and the load forward. Further examination on up and down movement of the backpack against the body of women during load carriage performance is needed.

Hip Muscle Strength and Women's Load Carriage Performance

We found that strength of hip muscles, specifically hip abductors, strongly predicted vertical COG excursion. A previous study showed that women preferred to carry a load around the waist by using strong leg muscles.[19] Probably due to strong upper body muscles, men preferred to carry loads in a different manner.[18] Obusek et al.[20] reported that men preferred to carry a backpack high and close to the trunk to decrease the energy cost. Hip abductors play an important role in stabilizing the pelvis and thus decreasing COG excursion during walking. Perry[24] stated that hip abductors are critical to laterally stabilize the pelvis over the hip and to control the vertical displacement of COG during walking. Previous load carriage studies on men and women did not examine the ability of muscle strength to predict load carriage performance. After completing a specialized strengthening program, Harman et al.[18] reported that physically active women showed significant improvement in lifting and load carriage performance. Harman's findings indicate that muscle strength is important for women's load carriage performance. Our findings show that MOLLE enables women to carry heavy loads by allowing them to use their strong leg muscles. However, we only investigated loads up to 50 pounds, whereas the load carriage demand for the U.S. Armed Forces personnel may be much greater. Future studies on heavier loads are indicated to further examine the role of leg muscle strength and women's load carriage performance.

Conclusions

MOLLE is a new load-carrying system developed by the U.S. Army Natick Soldier Center and adopted by both the U.S. Army in 2001 and Marine Corps in 1999. Load carriage performance of seven physically active women was examined using MOLLE at five load levels. Women can carry up to 50 pounds using MOLLE with similar load carriage performance as previously reported for male soldiers with MOLLE. Some women required modification of the padded hip belt to shift weight from the shoulders to the pelvis. Strong hip muscles are important predictors for women's load carriage performance using MOLLE.

Acknowledgments

We thank the following individuals for their participation in this study: Hsiao-Hsien Chen, Steven Yen, and Yu-Hui Tseng. The U.S. Army supplied the research team with the MOLLE used in this study.

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