Relation between Forward Lean and Ground Reaction Forces during Carrying Heavier Loads on Level Ground

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ABSTRACT

Load carriage is one of the key elements in dismounted military operations and is generally mission specific. Soldiers need to carry increasingly heavier occupational loads that may alter their gait mechanics, commonly affecting lower back, shoulders and lower limbs. Such responses, on long run, may impact on force generation and force sustainment, thus increasing the risk of injury. The loads are mostly carried in ensembles like backpacks (BP, 10.7kg) on back, haversack (HS, 4.4kg) and web (Wb, 2.1 kg) on waist and rifle (4.2kg) in hand or on shoulder, making a total of about 21.4kg. At times, depending on the operational requirement, they need to carry extra load in the BP. Present study measured the forward lean and ground reaction force responses in soldiers while they carried extra loads in the same BP designed for lower load. Twelve healthy male Indian Infantry soldiers with mean (SD) age 31.6(3.6)yrs, height 179.4(11.0)cm and weight 71.1(7.01)kg, volunteered for the study. They walked on a 10m walkway at self selected comfortable speed, without load and with carrying 21.4kg (existing load carriage ensembles, ELCe), 28.4kg (7kg added in BP) and 35.4kg (14kg added in BP), respectively. Their gait data were collected using 6 Camera based 3D Motion Analysis System and a pair of Kistler force plates. Results showed that forward lean and vertical ground reaction forces significantly increased when data for ELCe was compared with heavier loads carried in same BP. It may be concluded that putting more loads in the existing BP increases stress on musculoskeletal system leading to increased injury risk potential.

Key words: Heavy loads, Forward lean, Ground reaction forces, Joint injuries.

INTRODUCTION

Load carriage is one of the key elements in dismounted military operations and is generally mission specific. Soldiers need to carry increasingly heavier occupational loads that may alter their gait mechanics, commonly affecting lower back, shoulders and lower limbs. Such responses, on long run, may impact on force generation and force sustainment, thus increasing the risk of injury. Carrying heavy and unequally distributed load for long duration is known to cause physical, physiological and biomechanical stresses resulting in body soreness, aches, backpain, tiredness, exhaustion, burning out injury, march fractures and an overall loss of physical performance of the soldier (14). Some of the common ailments reported are foot blisters, cellulites or sepsis, metatarsalgia, stress fractures, patellofemoral pain syndrome, patellar tendinitis, bursitis, ligamentous strain, etc. The incidences of blisters have been found to increase with heavier loads, possibly due to causing more pressure on the skin and causing more movement of feet inside the boot due to increased propulsive and braking forces. Heavy loads may be a risk factor in low back injuries caused due to changes in trunk angles that may stress back muscles or sometimes these heavy loads may not move with synchronization to trunk resulting in cyclic stress of back muscles, ligaments and spine. Another widely reported load associated ailment is rucksack palsy which may be caused due to straps of backpack resulting into traction injury of C5 and C6 nerve roots of the upper brachial plexus (13).

The ability of soldiers to carry heavy load has been a subject of interest since many years. Infantry soldiers carry about 40 kg load in addition to their body weight for marching order that includes ration, water, ammunition, clothing, etc. In addition, they may carry radio sets and/or other electronic equipment weighing 10-15 kg or more for long duration. Injuries associated with load carriage may adversely affect an individual's mobility and reduce the effectiveness of the entire unit. It has been reported that soldiers often suffer from ailments associated with load carriage that are similar to those suffered by unskilled laborers lifting and carrying heavy loads to earn their livelihood (7). It was reported by Snook (1978) that load lifting and carrying represented principal sources of compensable work injuries in the United States.

Indian Infantry soldiers mostly carry loads in ensembles like backpacks (BP, 10.7 kg) on back, haversack (HS, 4.4 kg) and web (Wb, 2.1 kg) on waist and rifle (4.2 kg) or light machine gun (LMG, 6.8 kg) in hand or on shoulder. Generally this total load adds to 21.4 kg when they carry rifle. At times, depending on the operational requirement, they need to carry extra loads like radio sets and other communication equipments, ammunition etc. These extra loads they need to accommodate in the same BP. Present study therefore hypothesized that accommodating more loads in same BP will adversely affect the forward lean and ground reaction force responses in soldiers which may increase the injury potential of such operations.

METHODOLOGY

Subjects

Twelve healthy male Indian Infantry soldiers with mean (SD) age 31.6 (3.6) yrs, height 179.4 (11.0) cm and weight 71.1(7.01) kg, volunteered for the study. Subjects were given necessary information regarding the experimental procedure and they signed informed consent before commencement of the study.

Experimental Protocol

The Ethics Committee of the Institute approved the experimental protocol. Accordingly, subjects were first accustomed to gait laboratory and gait data collection procedure prior to starting the experiment. Then anthropometric data of each subject was recorded which included body weight (while wearing only underwear), height, right and left foot lengths and widths. For each subject the left and right static trials and walk trials with no load and load carriage maneuvers were collected on the same day. About 20 minutes' interval was allowed between two experimental conditions to overcome the fatigue effect. Six Raptor-H digital camera based 3D Motion Analysis System (M/s Motion Analysis Corporation, USA) interfaced with a pair of force platforms (M/s Kistler Ins., Switzerland) was used for collecting video and force data simultaneously. A set of 25 Helen Hayes retro-reflective surface markers was used for full body dynamic trials. Subjects wore only underwear and military boots during the experiment. Each subject was first asked to walk in the laboratory at his own comfortable pace before starting the experiment on a 10m walkway and the speed was noted. The subject was required to try and maintain that particular pace throughout the experiment. The walking speed of the subject in the beginning, middle and end of the Capture Volume, which was about 3m (common area of view for 6 cameras for recording gait data), was monitored by three pairs of infra-red photoelectric cells placed at 1.5 m apart from each other (3). The speed at which the subjects walked comfortably for different load carriage operations ranged from 0.97 to 1.1 $m.sec^{-1}$. They walked at self selected comfortable speed, covering about a distance of 2-2.5 km without load and while carrying 21.4kg (existing load carriage ensembles, Load 1, 30% of mean body weight), 28.4kg (7kg added in BP, Load 2, 40% of mean body weight) and 35.4kg (14kg added in BP, Load 3, 50% of mean body weight), respectively. Collected trials were then tracked and edited using Cortex 5.0 (M/s Motion Analysis Corporation, USA) software and subsequently exported to Orthotrak 6.26 software (M/s Motion Analysis Corporation, USA) for final processing and were normalized for body weight. The trials showing any distortion due to marker drop-out, obscuring or equipment failure were rejected even though such occurrences were rare. For each subject 4-5 good tracks with complete marker trajectories were finally selected for each condition and subsequently normalized for statistical analysis.

Parameters Studied

Mean (SD) values for trunk angular displacements and ground reaction forces (GRF) were recorded for three planes, viz., mediolateral, sagittal or anteroposterior and transverse or rotational/vertical. The GRF components were represented in Newton (N) and unit for trunk angular displacements was degree (°). The gait events at which these parameters were analyzed for normalized gait cycle were initial foot strike (FS1), midstance (MST), terminal stance (TS) and toe off (TO). These parameters were recorded for both right and left sides. However as no significant difference in the right and left side data was observed, in accordance with convention only right side data have been presented in this paper.

Statistical Treatment

One-way ANOVA using Statistical Package for Social Sciences (SPSS) for Windows (Release 16.01, USA) was performed to find out overall significant changes in the data. After ANOVA rejected the hypothesis of equality of the means for different load conditions, Bonferroni Post-hoc test was applied to find out whether each of the individual load was significantly different than the other at a significance level of $p \leq 0.05$.

RESULTS

The mean (SD) values of trunk angular displacements for right side of the body in three planes, viz., mediolateral, sagittal/anteroposterior and transverse/rotational/vertical planes at different events (FS1, MST, TS and TO) of normalized gait cycle are given in table 1. The mean (SD) values of ground reaction forces (GRF) in three planes, viz., mediolateral, sagittal or anteroposterior and transverse or rotational/vertical for right side of the body at different events (FS1, MST, TS and TO) of normalized gait cycle are given in table 2.

Trunk_Fwd_Tilt responses increased significantly at $p<0.05$ for all loads against NL and when lower loads were compared to higher loads. While walking without load, the trunk remained extended at all gait events, so that our subjects could maintain an upright posture. With the incremental increase of load in the same BP, there was a linear increase in trunk forward lean at different gait events. At FS1, i.e., at the starting of the gait cycle Trunk_Fwd_Tilt increased by 9°, 12.3° and 15.6°, respectively when NL was compared to Load1, Load2 and Load3. These changes as percentage were 391%, 536% and 678%, respectively.

Table 1: Trunk forward lean angles (°) in three planes at different events of gait cycle during load carriage operations (n=12)

	NL	Load1#	Load2#	Load3#
@Foot Strike				
Trunk_Lat_Tilt	2.8(0.41)	-1.7(0.23)	-0.57(0.15)	0.29(0.05)
Trunk_Fwd_Tilt	-3.1(0.33)	5.9(1.01)*	9.2(1.61)*$^{\delta}$	12.5(2.24)*$^{\phi\mu}$
Trunk_Rotation	-6.6(0.21)	-0.83(0.08)	-3.2(0.55)	-3.2(0.42)
@Midstance				
Trunk_Lat_Tilt	3.4(0.81)	1.1(0.06)	1.1(0.03)	1.0(0.02)
Trunk_Fwd_Tilt	-3.1(0.33)	4.4(0.91)*	7.1(1.84)*$^{\delta}$	14.4(2.65) *$^{\phi\mu}$
Trunk_Rotation	2.0(0.52)	3.9(0.92)	2.5(0.61)	-1.5(0.31)
@Terminal Stance				
Trunk_Lat_Tilt	3.4(0.39)	1.9(0.08)	1.9(0.09)	0.2(0.03)
Trunk_Fwd_Tilt	-2.3(0.08)	5.2(1.41) *	8.7(1.82)*$^{\delta}$	14.0(2.87) *$^{\phi\mu}$
Trunk_Rotation	-2.7(0.84)	4.5(0.91)	5.6(1.83)	-1.4(0.64)
@ Toe Off				
Trunk_Lat_Tilt	3.3(0.92)	1.3(0.09)	-0.37(0.01)	-1.3(0.08)
Trunk_Fwd_Tilt	-2.7(0.85)	5.6(0.88)*	9.4(1.81)*$^{\delta}$	12.7(2.53)*$^{\phi\mu}$
Trunk_Rotation	3.1(0.68)	2.6(0.49)	6.1(1.21)	-3.2(0.41) $^{\mu}$

\# Overall significance in right kinematics, p=0.05;
Bonferroni Post-hoc test significance:
* NL vs Load1/Load2/Load3, p=0.05;
δ Load 1 vs Load2, p=0.05; ϕ Load 2 vs Load 3, p=0.05; μ Load 1 vs Load 3, p=0.05

Table 2: Ground Reaction Force components (GRF, Newton) in three planes at different events of gait cycle during load carriage operations (n=12)

	NL	Load1	Load2	Load3#
@Foot Strike				
AP GRF	0	0.005(0.004)	0.034(0.02)	0.048(0.02)
ML GRF	0	-0.001(0.0002)	0.015(0.003)	0.021(001)
V GRF	0.42(0.05)	0.24(0.05)	0.38(0.03)	0.19(0.01)
@Midstance				
AP GRF	-0.09(0.002)	0.07(0.002)	-0.09(0.001)	-0.081(0.011)
ML GRF	0.06(0.025)	-0.07(0.012)	0.087(0.002)	0.085(0.0002)
V GRF	1.08(0.05)	1.4(0.07)*	1.4(0.05)*	1.5(0.07)*$^{\mu}$
@Terminal Stance				
AP GRF	0.014(0.002)	0.055(0.005)	0.086(0.002)	0.054(0.002)
ML GRF	0.042(0.006)	0.026(0.005)	0.062(0.005)	0.058(0.004)
V GRF	1.05(0.06)	1.36(0.09)*	1.41(0.05)*	1.61(0.06)*$^{\mu}$
@ Toe Off				
AP GRF	0.095(0.004)	0.7(0.06)	0.193(0.05)	0.283(0.018)
ML GRF	0.064(0.005)	0.103(0.002)	0.091(0.004)	0.046(0.002)
V GRF	1.14(0.06)*	1.42(0.06)*	1.47(0.16)*	1.64(0.09)*$^{\mu}$

\# Overall significance in right kinematics, p=0.05;
Bonferroni Post-hoc test significance:
* NL vs Load1/Load2/Load3, p=0.05;
δ Load 1 vs Load2, p=0.05; ϕ Load 2 vs Load 3, p=0.05; μ Load 1 vs Load 3, p=0.05
AP GRF– Anteroposterior GRF; ML GRF : Mediolateral GRF; V GRF : Vertical GRF

However main focus of this study was to see the gait responses when more loads were put in the same BP. At all events, Trunk_Fwd_Tilt responses increased significantly for Load 1 compared to Load 2 (56%), Load 2 compared to Load 3 (36%) and Load 1 compared to Load 3 (112%) at FS1. At MST these changes were 37%, 103% and 227%, respectively; at TS 67%, 61% and 158% respectively and at TO these changes were 67%, 59% and 127%, respectively. These data show that maximum increase in trunk forward lean occurred at MST. The changes in mediolateral and anteroposterior GRF at all events were not significant in any load condition and did not show any linearity or proportionality. The changes in vertical GRF showed linear and proportional increase in magnitude, which were significant when NL was compared to each load conditions. However, when load 1, load 2 and load 3 were compared among each other with respect to vertical GRF, the changes were not significant at any event except for Load 1 vs Load 3 at MST, TS and TO.

DISCUSSION

Results of this study indicate that trunk forward lean (Trunk_Fwd_Tilt) in sagittal plane played very important role in maintenance of optimized body posture while walking with moderately heavy loads and these changes in posture to facilitate walking with extra load took place at all gait events studied with maximum at MST. This observation corroborates with results earlier reported by the authors on low magnitude military loads which stated that at MST when body transferred load from one leg to other, significant trunk forward lean showed that trunk moved anteriorly to counterbalance the loads on the back (17). Similar observations were reported by other past studies e.g., Hong and Cheung (2003), Attwells et al. (2006). Stuempfle et al. (2004) stated that placement of loads in the load carriage ensemble was also an important consideration for efficient load carriage.

Present study indicated that while walking with load, the stance phase leg had already absorbed the extra load at TS and at TO it was ready to go into swing phase. Similarly, Hong and Cheung (2003) investigated the biomechanical parameters of school children of 9-10 years age while walking with loads of 20% body weight (BW) and suggested that permissible BP loads for the school children should not exceed 15% of BW. They recommended that trunk inclination should be considered critically for deciding permissible loads for a given population. It is known from past studies that carrying load in BP for long induced deviations from natural postures of trunk, causing discomfort in the upper body and low back injury (6).

Several researchers earlier reported that while carrying heavier loads, an increase in forward lean of the trunk was observed (1, 11). These studies reported that an increase in load always induced forward lean of trunk which is necessary to counterbalance the hip moments and to stabilize body's centre of mass (CoM). This was achieved by increase in forward inclination, helping the body to minimize the energy expenditure of load carriage and increase the efficiency of walking process (5). Though an upright posture is considered more efficient when carrying load, it could inhibit forward advancement of the body with load on the back (11, 18, 19). Study by Majumdar et al. (2010) found BP caused about 10° forward lean while soldiers walked with BP (10.7kg).

In the present study, the mediolateral and anteroposterior components of GRF did not show significant change in any condition when load conditions were compared with either NL or among the load conditions. The changes observed were too small and unrelated to increase in load magnitude. This observation corroborated previous studies (4, 9, 15, 12). Birell et al. (2007) studied the effects of incremental military load on GRF parameters and found that load added in 8kg increments caused the vertical and anteroposterior GRF parameters to increase linearly and proportionately. Other studies reporting similar observations were Majumdar et al. (2013), Birrell et al. (2007), Birrell and Hooper (2005), Lloyd and Cooke (2000b), Kinoshita (1985), Kinoshita and Bates (1981), etc. However, present study showed similar results for vertical GRF component only.

While walking with load, higher impact forces are experienced due to higher weight being over the striking foot at the time of initial contact. This may cause shifting of body's centre of mass (CoM) anteriorly, increasing positive GRF. Load is said to impede normal functioning of lever system involved in the final push-off of the body and might expose metatarsal bones to prolonged mechanical stress. These changes are major risk factors in overuse injuries, like stress fractures of the tibia, metatarsals and knee joints (3, 11). These studies suggested that increased GRFs, particularly in the vertical plane, could result in overuse injuries, though these authors could not ascertain the overuse injury potential of these load carriage operations. Goh et al. (1998) reported that maintenance of stability and effective progression resulted in higher peak lumbosacral forces when carrying load in BP. Birrell and Haslam (2008) found 2% increase in forces at heel strike (FS1) for carrying a rifle of 4.2kg. For same load, Majumdar et al. (2013) reported 6% increase in impact forces at heel FS1 in Indian soldiers. Therefore, when loads are being added in the same BP (10.7 kg, 17.7 kg and 24.7kg) beyond it's normal carrying capacity and when the placement of these loads are not compact as suggested by Stuemple et al. (2004), CoM may be displaced in such a way that the soldier is required to increase forward lean more to counterbalance the increase in system weight. Increased vertical GRF is therefore compensated effectively by increased forward inclination for maintaining balance and forward advancement of the body, as observed in present study.

CONCLUSIONS

It can be concluded from observations of the present study that carrying extra load in the same BP, as is currently done by Indian soldiers, caused significant increase in trunk forward lean and vertical GRF, which may increase stress on musculoskeletal system and overuse injury risk potential. Therefore, more loads should not be added in the BP than the magnitude for which it is designed to avoid health risk of the individual.

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