1. Introduction

The effect that military load carriage has on ground reaction force (GRF) parameters has been examined previously in the literature (Birrell et al, 2007; Harman et al, 2000; Kinoshita, 1985; Lloyd and Cooke, 2000a; Polcyn et al, 2002; Tilbury-Davis and Hooper, 1999). However, less attention has been paid to the distribution of load on the body, particularly with respects to the biomechanical changes of gait. It has long been suggested that the most efficient way to load the body is by keeping it as close as possible to the body's CoM, while also utilising the larger muscle groups (Legg and Mahanty, 1985). However, due to various ergonomic reasons the backpack is the only really viable option for members of the military to carry their own equipment. Research has shown that placing load closer to the body's CoM results in a reduction in energy cost (Abe et al, 2008; Coombes and Kingswell, 2005; Datta and Ramanathan, 1971; Lloyd and Cooke, 2000b), with a more upright walking posture being adopted (Kinoshita, 1985; Harman et al, 1994). In terms of the kinetic effects a reduced maximum braking force and stance time, while increasing force minimum are reported outcomes as a result of distributing load around the trunk (see references below). The actual implications that these changes to basal gait patterns have to injury or energy cost is relatively unknown. However, we can postulate that a decrease in maximum braking forces may have a positive effect on blister development, due a reduction in the sheering forces applied to the foot-boot interface when walking. In addition, sports research has shown that a reduction in horizontal braking forces can facilitate the forward advancement of the body during running (c.f. Ciacci et al, *In Press*), this principle may also relate to long distance marches with heavy loads in military situations. High magnitudes or volumes of impact forces (or force produced at heel strike), like those experienced during load carriage or running, are a major risk factor for overuse injuries. In particular, stress fractures of the tibia and metatarsals and knee joint problems (Cavanagh and Lafortune, 1980; Polcyn et al, 202). A reduction in either of these two parameters would have clearer implications on injury as a result of load distribution.

To the author’s knowledge only five studies have investigated some aspects of load distribution on GRF parameters, including just three papers in peer-reviewed journal (Kinoshita, 1985; Lloyd and Cooke, 2000a, Hsiang and Chang, 2002), one military report (Harman et al, 2001) and one conference paper (Koulmann, 2006). These available studies have generally been restricted to between 4 and 6 load and carrying system combinations, with limited mechanisms put forward for the observed changes. The aim of this study is to build on and develop this current knowledge by investigating the effect that different distributions of carried load had on kinetic (specifically GRFs) parameters of human gait. This current study will use an increased number of load and backpack combinations (four different loads and three different backpack systems), and also military specific load carrying systems, while offering links to previous research to develop the implications of these changes to basal gait patterns.

2. Methodology

2.1 Participants and Equipment

Twelve male participants volunteered for the study (mass 81.3 kg ± 9.9 S.D., height 184.4 cm ± 6.2, age 29.2 years ± 9.0). All participants volunteering for the study had previous experience carrying military style backpacks, all were right foot dominant and rear-foot strikers. A verbal and written explanation of the study was given, after which a health screen questionnaire was completed. Finally signed, informed consent was obtained from all participants before commencing the trial.

Kinetic data were collected when participants walked over a Kistler force plate (Type 9286A; Kistler Group, Winterthur, Switzerland) in conjunction with a Coda Mpx30 motion analysis system (Charnwood Dynamics Ltd, Rothley, Leics, UK), with data sampled at 400 Hz. The force plate was embedded flush in an 8.4 m walkway, situated halfway along the walkway and slightly off centre. This gave adequate distance before and after the force plate to achieve a natural gait pattern. The target walking speed throughout was 1.5 $m.s^{-1}$ (± 5%), and measured using three pairs of infra-red photoelectric cells (Brower SpeedTrap II; Brower Timing Systems, Draper, Utah, USA). One set recorded speed on approach to the force plate and the other speed after the force plate. Both speeds had to be within the desired range, thus limiting the potential for acceleration or deceleration that would affect the GRF produced. To assess the differences caused by altering the load distribution three military load carriage systems (LCS) were adopted (figure 1), and 4 different loads were carried 8, 16, 24 and 32 kg, these are absolute loads and not dependent on participants body mass. In addition to the load, a weighted replica SA80 assault rifle was carried in all testing conditions. The rifle condition also formed the control, or baseline, for the study. It was deemed essential for a rifle to be carried during this study as military personnel will almost always carry a rifle with loads when on training and operations. Also, rifle carriage has been shown to change basal gait parameters, reflected by changes to ground reaction force parameters (Birrell and Haslam, 2008).

The three LCS used for this study were:

1. Backpack LCS – Load solely carried in the '90 Pattern short back Bergen.
2. Standard LCS – This utilised the standard issue UK '90 Pattern Short back Bergen and PLCE waist webbing.
3. AirMesh LCS – This consisted of AirMesh Prototype III Bergen and PLCE vest webbing.

Insert Figure 1 Here

2.2 Protocol

Each participant completed 13 experimental conditions (table 1), with the order in which the participants completed the conditions fully randomised. Ten successful trials were required for each condition. A trial was deemed successful if the speed was attained, the foot struck cleanly on the force plate and if an un-adjusted gait pattern was maintained. Participants were asked to wear light, non-restrictive clothing and wore standard issue British military leather boots supplied by the experimenters. To ensure the participants had familiarised themselves with the protocol an unlimited number of practice trials were allowed.

Insert Table 1 Here

The use of the conditions outlined in table 1 had the effect of progressively distributing load more evenly around the trunk. Although the body's CoM was not measured it is readily apparent that the 3 LCS adopted with this study significantly altered its position (figure 1). The backpack LCS displaces the CoM furthest away from its neutral position, with all the load carried on the posterior of the body. The standard LCS then starts to modify this with a proportion of load placed around the hips. Finally, the AirMesh LCS distributes load on both the anterior and posterior of the body. This system results in the least displacement of the body's CoM from its neutral position. An aim of the study was to replicate military load carriage. Therefore the 8 and 16 kg loading conditions this load was carried in the webbing, either vest webbing in the AirMesh LCS or waist webbing in the Standard LCS. As stated previously with the Backpack LCS load was always carried in the backpack alone (figure 1). Load distribution within each LCS replicated how they would be packed by military personnel, i.e. the CoM of each backpack was as close to the middle of the pack as possible. With webbing realistic distribution of load was also achieved with the bulk of the weight in the larger side pouches of both the vest and waist webbing, with the rest of the load evenly distributed around the remaining pouches.

2.3 Parameters Measured and Data Analysis

Eight GRF parameters were collected, these were: Impact peak, force minimum, thrust maximum and vertical impulse in the vertical axis; maximum braking and propulsive forces in the anteroposterior axis; mediolateral impulse; and stance time. The participant's kinetic data were normalised and expressed as Newton's per unit body mass ($N.BM^{-1}$), allowing direct comparison between participants. This normalisation included the weight of the participant, rifle and any load carried. For each parameter measured, a 10-trial mean was calculated for each participant and then used in the analysis. A MANOVA was used to determine differences between conditions, with a Tukey post-hoc test were used to compare the 3 LCS (standard, AirMesh and backpack) at the different carried loads. The statistical testing was conducted in SPSS 12 for Windows (SPSS Inc., Chicago, IL, USA) and significance was accepted at $p<0.05$.

3. Results

Results from the study showed that only the thrust maximum (aka force produced at toe-off in the vertical axis) showed a significant main effect ($p<0.05$) for the 3 LCS with the MANOVA (table 2). The results indicate that the thrust maximum force produced during the Backpack LCS condition was significantly lower than those produced during the other two conditions (Standard and AirMesh LCS). In addition to this main effect the Tukey post-hoc test highlighted other significant differences between the 3 LCS at different carried loads. Firstly, a reduction in maximum braking force (in the anteroposterior axis) when a load of 32 kg was carried in the AirMesh LCS (weight distributed on the anterior and posterior of the body) was observed. With single support (aka stance time) also showing changes with the three LCS at differing loads. Important findings from the study are summarised in table 2.

Insert Table 2 Here

4. Discussion

This study utilised 12 different load and LCS combinations, and carried load in British military LCS. These factors make the current study both relevant and significant in aiding our understanding of the biomechanical effects of military load carriage. The most important findings from the study are described below.

1. A significant change in the thrust maximum was observed between the 3 LCS. More specifically, the backpack LCS produce a lower force compared to the standard LCS at all loads. Also, a trend was observed for thrust maximum in the backpack LCS to be lower than the AirMesh LCS at the higher loads.
2. Stance time was significantly lower in the backpack LCS compared to the standard LCS at 32 kg, with a trend to be lower at 24 kg. Also, a trend was present for the AirMesh LCS to produce a lower stance time to both the other systems at 8 kg.
3. Maximum braking force was significantly reduced in the AirMesh LCS condition compared to the Backpack and Standard LCS when carrying 32 kg.

4.1 Changes Observed to the Thrust Maximum

The thrust maximum (or force produced at toe-off measured in the vertical axis) displayed an overall effect for significant differences between each of the three LCS, the post-hoc test also revealed differences between the loads. Figure 2 shows the backpack LCS condition resulting in lower forces compared to the standard LCS at all carried loads, and around larger reduction in force compared to the AirMesh LCS at the higher loads. This implies that shifting the CoM posteriorly by carrying load on the back reduces the force at toe-off. These differences observed may be equally attributed to the forward lean of the participant while walking with the loads, as it is with the changes to the CoM. Forward lean is the body's way of balancing out the moments caused by adding additional load to the posterior of the body. The greater the load or the further away this load is placed from the body's neutral CoM, the greater the forward lean (Attwells et al, 2006; Harman et al, 2000; Polcyn et al 2002).

Insert Figure 2 Here

It is reasonably well established that distributing load on both the anterior and posterior of the body reduces forward lean during load carriage (Kinoshita, 1985; Harman et al, 1994; Fiolkowski et al, 2006). Kinoshita (1985) suggested that the inclined posture adopted with a backpack system appears to facilitate forward advancement of the body, while the double-pack system inhibits this advancement. Applying this idea to the results found with this current study implies that displacing the body's CoM posteriorly increases the forward lean, which in turn facilitates forward advancement. Thus reducing the forces needed to advance the body during mid-stance and into toe-off. This suggests that forward lean increases the passive momentum of the body resulting in reduced forces at toe-off. A notion supported in part with results from this study which showed significant decreases in force produced at toe-off when carrying loads in a military backpack. A similar principal was observed by Harman et al (2001), but instead of a lower thrust maximum they found the force minimum was decreased when the body's CoM was displaced further away from its natural position. Kinoshita (1985) also suggested that a double-pack system may produce more vertically orientated force vectors when compared to the backpack system due to the more erect walking posture. Again this may be as a result of the more erect walking posture associated with the double-pack. Specifically with Kinoshita's study this was suggested in response to the greater force minimum observed with the double-pack. However, it may be just as relevant with respect to the current study and the significant increase in thrust maximum force seen when carrying load in the standard LCS.

As well as the potential factors of CoM and forward lean causing the observed differences in the thrust maximum force other features of gait may also cause or augment these changes. For example, modifications to stride parameters may also be responsible for the observed changes in GRF. Harman and colleagues showed in two separate studies that stride length was shorter when load was distributed more evenly around the body compared to a more traditional backpack (Harman et al, 1997 and 2001). They suggested that an increased stride length is seen when the CoM is moved further away from its neutral position. A longer walking stride usually indicates that the foot is placed further in front of the body, an action which is associated with increased braking forces (Martin and Marsh 1992; Harman et al, 2001) and impact forces (Challis, 2001). In other words, longer stride lengths lead to greater force produced during the heel strike phase of the gait cycle. In response, a lower force minimum may be observed as active momentum has been generated in the initial phase of the gait cycle facilitating forward propulsion (Hsiang and Chang, 2002). This was proposed by the authors to be in accordance with the inverse pendulum model described by MacKinnon and Winter (1993). This in turn leads to reduced momentum being needed to advance the body during mid-stance and toe-off, in this circumstance leading to a reduction in the respective forces. This factor may also be responsible for the differences observed with respect to the thrust maximum with the current study.

In addition to the statistically significant differences observed between the backpack and standard LCS, a trend with the data was seen for the backpack LCS to produce lower forces compared to the AirMesh LCS at the higher loading conditions of 24 and 32 kg. The potential reasons put forward previously (forward lean and changes to stride parameters) are equally as relevant when considering the AirMesh and backpack LCS. It is however of interest that the AirMesh LCS does not produce significant differences compared to the backpack LCS, even though the difference in the CoM is more apparent than with the standard LCS.

4.2 Changes Observed to Stance Time

The three different LCS adopted during this study resulted in changes to the stance time, or length of time the right foot was in contact with the floor. The post-hoc test revealed that stance time for the backpack LCS condition was significantly shorter than the standard LCS condition at 32 kg, and a trend for a difference at 24 kg of carried load. A trend was also seen for the AirMesh to result in a shorter stance time compared to both the backpack and standard LCS when 8 kg were carried (figure 3). Of the five studies found to investigate the effects of load distribution on the kinetics of gait, only two (Kinoshita, 1985; Lloyd and Cooke, 2000a) reported stance time as a parameter. Kinoshita's study found no significant difference in stance time when carrying either 20 or 40% of bodyweight in a backpack or double-pack. However, an observable trend in the mean was noted for the backpack condition to exhibit slightly longer single support times compared to the double-pack system. Lloyd and Cooke also noted a trend (p=0.056) for the double-pack to elicit a shorter stance time than a traditional backpack. Both these studies suggest that loading the body more evenly during load carriage leads to reduced single support times.

Insert Figure 3 Here

Results from this current study showed that at 8 kg of carried load the AirMesh (or double-pack) LCS showed a trend to produce lower single support values compared to the other systems used (figure 3). This is in support of other research which also observed trends for double-packs to result in reduced stance times compared to traditional backpacks when walking (Kinoshita, 1985; Lloyd and Cooke, 2000a). Neither of these two studies suggested potential mechanisms behind these observed trends. A potential reason for this observed difference was put forward by Birrell et al (2007) who suggested that stance time is longer when carrying load in a backpack due to the extra time it takes to shift the CoM (which has been displaced further posteriorly with the backpack and standard LCS) over the base of support and into the propulsive phase. Another mechanism for longer stance times may be the need for extra stability. The body's CoM is displaced further away from its neutral position in the standard and backpack LCS conditions compared to the AirMesh LCS condition. Research suggests that when load is placed close to the body's CoM it results in an increase in static stability (Schiffman et al, 2006).

At the higher carried loads the backpack condition exhibited a trend for lower stance times compared to the other two LCS conditions (figure 3). These results contradict suggestions made by previous researchers and supported in part by this study. This is that loading the body more evenly during load carriage leads to reduced single support times. A potential reason for this difference may be psychological and comfort issues overriding the biomechanical parameters. Anecdotal reports from the participants in the trial were that carrying 24 and 32 kg in the backpack alone was very uncomfortable. Efforts were made to distribute the weight evenly within the backpack, but the load was still a considerable 'lump' that was pulling backwards on the shoulders. These comfort factors may have combined to significantly change participant’s gait cycle, thus overriding the biomechanical effects such as changes in the position of the boy’s CoM or forward lean.

4.3 Changes Observed to the Maximum Braking Force

Maximum braking force is the force that slows the body down during the initial part of the gait cycle and acts in the anteroposterior axis. The main interest with this parameter in respect to LCS design is that increased sheer forces that act on the foot will ‘increase the probability of blisters during physical activity’ (Knapik et al, 1997a). Foot blisters are the most common load carriage related injury and can also be debilitating (Knapik et al, 1997b; Reynolds et al, 1999). Load carriage has also been shown to increase blister incidence independently to other factors, with Knapik et al (1997a) suggesting that load carriage increases the pressure on the skin and causes more movement between the foot and boot through higher propulsive and braking forces, thus increasing the risk of blister occurrence.

Insert Figure 4 Here

Figure 4 shows the significant ($p<0.05$) increase in maximum braking force with the backpack condition compared to both the standard and AirMesh LCS conditions at 32 kg. This increase in force is more marked than previous results, with the backpack showing a considerable 10% increase in maximum braking force compared to the other two LCS. This suggests that carrying load that is more evenly distributed around the trunk reduces such forces, this has been observed with other studies (Kinoshita, 1985; Harman et al, 2001). Factors given for this increase are as a result of the more erect walking posture with the double-pack producing more vertically orientated force vectors (Kinoshita, 1985) or due to an increase in stride length with a double pack (Harman et al, 1997 and 2001). Lloyd and Cooke (2000a) published results that were in contrast to the above findings. They reported no significant differences with the maximum braking force with a backpack compared to double-pack, but instead increases to the maximum propulsive force. A suggestion put forward by the authors for the increase in propulsive force with the backpack condition was that this resulted from a decrease in forward lean through the stride cycle. They conclude that the greater the change in positive and negative forward lean (or greater range of motion of the trunk) observed in double-pack condition may lead to a difference in momentum of the upper body, which could reduce propulsive forces (Lloyd and Cooke, 2000a).

The most likely reason for the increase in maximum braking force in the backpack condition seen with this study is either the increase in forward lean or increased stride length. Both of these factors have been shown by other studies to be possible reasons for such increase. The important role that increases in maximum braking force play in the development of blisters is highlighted again in a study by Knapik et al (1997b). Twenty-one Special Forces soldiers performed 6 individual road marches carrying three loads (24, 48 and 61 kg) and two pack systems (a standard military LCS and an experimental double-pack). Results showed that blister incidence was lower when carrying 61 kg in the double-pack compared to backpack. Also seen was a decrease in lower back discomfort but subsequent increases in neck and hip discomfort. This current study can confirm that the most likely mechanism behind this lower blister occurrence is as a result of a decrease in maximum braking force resulting in a reduction in sheer forces acting at the foot-boot interface.

5. Conclusions

Changing the distribution of load within the military LCS used in this study had limited effect on the GRF parameters of human gait. Despite this important findings were established, in particular the effect of heavy load carriage on maximum braking force. A 10% increase in maximum braking force was observed when carrying 32 kg in the backpack condition compared to the other two conditions used – the importance here lies in the development of blisters. The thrust maximum, or force produced at toe-off, was the only parameter to differ significantly between the three LCS adopted for the study. Displacing the body's CoM further away from its neutral position, as induced by the backpack LCS, resulted in a decrease in the thrust maximum force. This may be perceived as a positive outcome for posterior load carriage, which may have been the case if the considerable negative impacts on braking forces, as mentioned above, were not as a direct consequence. Finally, stance time with the backpack LCS was shorter than in the other two conditions at the heavier carried loads. This may be a result of the uncomfortable nature of carrying such heavy loads in a backpack alone.

The carriage of load in a double-pack has significant benefits when considering the kinematics and energetics of load carriage. In addition to these, the reduction of braking forces is a considerable kinematic benefit of carrying load in such packs. Although the total load carried may still be considered the major cause of changes to gait patterns or increases in injury rates, the scientific testing of and development of future LCS can modify these risks. Particular focus in future LCS designs should be placed on reducing the impact peak and maximum braking force, as these have the strongest and most viable links to the development of both acute and overuse injuries. Using a double pack is once such method to reduce these risks.

Acknowledgements

The authors would like to thank Dr Robin Hooper for his help and advice, which were a major contribution to this study.

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