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BIOMECHANICAL DIFFERENCES ASSOCIATED WITH TWO DIFFERENT LOAD CARRIAGE SYSTEMS AND THEIR RELATIONSHIP TO ECONOMY

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ABSTRACT
Purpose. To explore relationships between load carriage economy and the kinematics and kinetics of load carriage using both a backpack (BP) and a double pack (DP). **Basic procedures.** Nine participants walked on a treadmill at gradients of between 27% downhill and 20% uphill, and over a force plate on level ground, at a speed of 3 km.h-1. Expired air was collected throughout the treadmill experiment and all experiments were filmed for subsequent biomechanical analysis. The relative economy of load carriage was expressed in terms of the Extra Load Index (ELI). **Main findings.** There was a tendency for the double pack system to be associated with better economy than the BP. The double pack system provoked significantly less forward lean than the backpack and the horizontal displacement of the CoM was also smaller for the double pack system and both of these factors were strongly related to economy. There was, however, a greater range of motion of the trunk in the DP condition and this was also associated with improved economy. **Conclusions.** The results suggest that the DP was associated with smaller perturbations in gait than the BP and that this represents an advantage in terms of economy. In particular freedom of movement of the trunk in the sagittal plane may be an important consideration in the efficiency of load carriage systems.

Key words: load carriage, economy, kinematics, kinetics

Introduction

There is now a considerable body of research relating to human load carriage. Much of the published research has been comparative in nature, considering metabolic (e.g. Abe et al. [1], Bastien et al. [2]), kinematic (e.g. Coombes and Kingswell [3], Attwells et al. [4]), Kinetic (Birrell and Haslam [5], Hsiang and Chang [6]), EMG (e.g. Motmans et al. [7], Hong et al. [8]) and subjective perceptual (e.g. Mackie and Legg [9], Lloyd et al. [10]) differences between load carriage systems. There appears to be some consistency in the literature in relation to the potential advantages of load carriage systems that spread the load around the trunk, and in particular double or front/back pack systems. A number of studies have reported advantages in terms of economy over both traditional backpacks (e.g. Lloyd and Cooke [11] and other carrying methods (e.g. Datta and Ramanathan [12], Legg and Mahanty [13], Coombes and Kingswell [3]). A more limited number of studies have compared either the kinematics (Kinsohita [14]) or the kinetics (Kinoshita and Bates [15], Kinoshita [14], Lloyd and Cooke [16], Hsiang and Chang [6]) of walking whilst carrying a load using a double pack system with either a backpack or unloaded walking. All of these studies have concluded that the perturbations in gait pattern associated with a double pack system are less than those associated with back-loading.

There have been a number of reports in the literature in which empirical data relating to both economy and biomechanical adaptations have been presented (e.g. Quesada et al. [17], Malville et al. [18], Coombes and Kingswell [3]). There are, however, very few papers that have attempted to relate biomechanical changes to measures of economy (Obusek et al. [19], Schiffman et al. [20]). This may be a serious omission as it has recently been suggested that individual variability in load carriage economy may be much greater than previously reported and worthy of further investigation (Lloyd et al. [21]). One way in which this might be achieved is to explore relationships between economy and the acute perturbations to gait associated with different load carriage systems.

The purpose of this paper is, therefore, twofold. Firstly, it will add to the relatively sparse literature relating to the kinematics of double pack systems. Secondly, it will seek to explore relationships between the biomechanical and physiological changes associated with load carriage using both a backpack and a double pack. This will include a reinterpretation of a previously

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published physiological comparison (Lloyd and Cooke [11]) using a measure of relative economy, the Extra Load Index (ELI) (Lloyd et al. [22], based on the earlier work of Taylor et al. [23]. The relationships between ELI, previously reported kinetic changes (Lloyd and Cooke [16]) and new kinematic data will also be considered.

Materials and methods

Participants

Nine healthy volunteers took part in this study, five female and four male. All participants had previous experience of walking with backpack loads. On average the groups were 24.7 ± 4.3 years of age. Average stature and mass were 172.7 ± 11 cm and 73.4 ± 16.4 kg respectively. Body Mass Index (BMI) was, on average, 24.35 ± 2.55 kg · m^{-2} and none of the participants were obese (all BMI < 30). All participants gave informed consent prior to beginning the study, which had received ethical approval from the Leeds Metropolitan University Ethics Committee. A screening questionnaire was administered to ensure that no participants should have been ruled out on health grounds including known musculo-skeletal or neurological conditions that may have impaired their ability to undertake the tests. The participants were of at least average cardio-respiratory fitness with $\dot{V}O_{2max}$ values of 45.46 ± 4.48 ml · kg · min^{-1} for the females and 53.74 ± 9.95 ml · kg · min^{-1} for the males.

Design

Participants were given the opportunity to accustom themselves to both treadmill walking and load carriage with each of the two packs via an habituation session lasting for a minimum of 20 minutes. The study involved participants being tested on five occasions, each one week apart. The first test assessed the participants' $\dot{V}O_{2max}$, the next three tests involved treadmill walking in each of three conditions: unloaded, double pack and backpack. The order in which the loading conditions were undertaken was randomised via a Latin square design with participants randomly assigned (by drawing lots) to one of three groups. Full details of testing protocols and data reduction have previously been published (Lloyd and Cooke [11]). The final test involved participants walking over a force plate and order of loading mirrored that of the preceding three tests. Participants were instructed to look straight ahead whilst walking and to maintain a natural gait. A trial was only deemed acceptable if three conditions were met: the participant's right foot must have landed wholly within the boundaries of the force plate; there must have been no alteration to normal walking gait; and the recorded time for the trial must have been within ± 5% of the target time. If the first of these conditions was not met the starting point of the participant was adjusted accordingly before the next attempt. If the second or third conditions were not met the participant was given suitable advice and asked to repeat the trial. The participant continued to walk unloaded along the runway until three acceptable trials (e.g. Chow et al. [24], Harman et al. [25]) had been achieved. Full details of the protocol for this element are described in Lloyd and Cooke [16].

Equipment

Two packs were used in this study: a double pack (DP) (AARN designs, NZ) and a traditional backpack (BP) (Karrimor Alpiniste, Karrimor, UK). Both packs had a capacity of 65 litres and the double pack came supplied with front balance pockets. The packs were filled with equipment, food and water suitable for a trip lasting one week. Since this load is independent of participant body mass, the total mass of pack and contents was 25.6 kg in all cases. This absolute load equated to an average relative load of 36.2 ± 6.7% Body Mass. Adjustments for differences in the weight of the packs themselves were made by manipulating the food and water rations.

Filming procedures

All filming was performed with a video camera (Panasonic, Japan) operating at 25 Hz. During the force plate experiment the camera was placed perpendicular to the line of walking and 7.5 m from the force plate. Prior to the filming of each subject a marked reference scale was placed on the force plate and filmed to allow for scaling during subsequent analysis. Participants were also filmed standing still on the force plate prior to the start of each loading trial. During the treadmill tests the camera was placed perpendicular to the line of walking at a distance of 5 metres from the treadmill and scaling was achieved via known distances on the treadmill frame.

Data analysis

Video film was digitised field by field, producing an effective sampling rate of 50 Hz, employing the body segment model for adult males according to Dempster

[26] based on 17 points. From the digitised data position of the centre of mass and co-ordinates of the shoulder, hip, knee and ankle joints were then calculated (Mmotion Digit, UK). Data was smoothed via a low pass butterworth filter (6 Hz) prior to analysis. All statistical analyses were performed using SPSS v17.0 (SPSS inc.).

The position of the centre of mass (CoM) for each subject in the standing position was calculated ignoring the mass of the pack. The position of the centre of mass was expressed in relation to the position of the right ankle joint (Mackie and Legg [9]). This was done to eliminate the problems of locating a single reference point for all participants and the slight differences in standing positions. Analysis of the change in position of the centre of mass from the unloaded condition for each pack in both the horizontal and vertical directions was performed using paired sample *t* tests.

Trunk angle has been defined as the angle between the line joining the right hip to the right shoulder and the horizontal, i.e. 90° represents a vertical trunk position, angles less than 90° indicate forward lean. Trunk angles were calculated at the heel strike, mid support and toe off phases of the foot contact with the force plate. They were also calculated for the same points of the gait cycle at the extreme uphill, extreme downhill and level walking conditions of the treadmill protocol. To provide a single value for trunk angle whilst walking the mean value of these three points was calculated. Change in forward lean was defined as the difference between the trunk angle in the unloaded condition and the trunk angle in the loaded condition. Comparison of the changes in forward lean associated with each pack was performed via repeated measures ANOVA. Significant main effects were further explored using pairwise comparisons with a Bonferroni correction

Stride frequency was calculated from the video recordings of the treadmill protocol. The number of frames between right toe off and right toe off were counted for 10 complete stride cycles at each gradient of the treadmill protocol and mean values calculated. Stride length was then calculated based on the known treadmill speed and the relationship between stride length, stride frequency and speed. Differences in stride length were assessed via ANOVA with repeated measures with *post hoc* analysis using the Bonferroni correction.

The relative economy of load carriage in each condition at each gradient was expressed in terms of the ELI and calculated as follows:

$$\text{ELI} = \frac{\text{mlO}_{2L} \cdot \text{kg total mass}^{-1} \cdot \text{min}^{-1}}{\text{mlO}_{2U} \cdot \text{kg body mass}^{-1} \cdot \text{min}^{-1}}$$

where mlO_{2U} and mlO_{2L} refer to unloaded and loaded oxygen consumption respectively. Differences in ELI were explored via ANOVA with repeated measures and *post hoc* analysis as previously.

Pearsons Product Moment Correlation Coefficients were calculated to explore the relationships between relative economy (ELI values) and various kinematic and kinetic variables for level walking.

Results

Relative economy

Mean + s ELI values are shown in Figure 1. Considering all gradients there was a tendency for the double pack to be associated with lower ELI values (better economy) than the backpack (mean difference 0.076, $p = 0.092$) and this was consistent across all gradients (loading condition × gradient interaction, $p = 0.672$). Figure 1 also indicates that there was considerable individual variation in response. Coefficients of variation for ELI in the level walking condition were 16.1% and 15.2% for DP and BP respectively. Similarly there was individual difference in the response to the two loading conditions with only a very weak, and non-significant relationship between the ELI values (level walking) of $r = 0.373$ ($p = 0.323$).

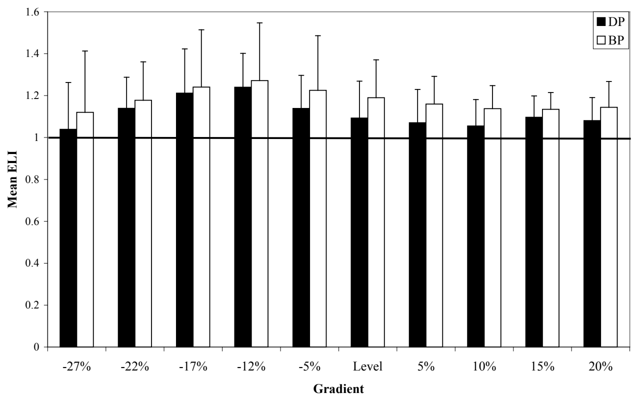

Figure 1. Mean + s ELI values in each condition at each gradient

Stride length

Mean + s values of stride length (m) at each gradient are shown in Figure 2. Considering all gradients, the stride length associated with unloaded walking was on average 5 cm longer than that associated with the DP ($p = 0.010$). It was also longer than that associated with the BP, but not significantly so (mean difference 3.2 cm, $p = 0.203$). Considering all conditions, the stride length during level walking was significantly greater than that

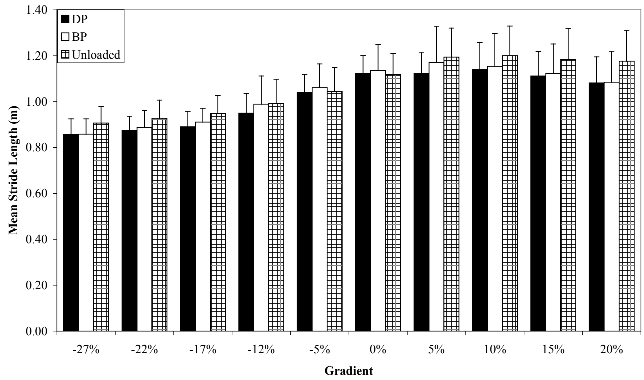

Figure 2. Mean + s stride length (m) in each condition at each gradient

during downhill walking ($p = 0.001$) with the mean differences increasing as the slope became steeper (7 cm at –5% to 25.2 cm at –27%). There was, however, no significant difference between the stride length on the level and any of the uphill gradients ($p = 1.000$). The stride length for the unloaded condition remains relatively stable across all the uphill gradients whilst the two loading conditions are associated with reductions in stride length at the two steepest gradients (loading condition × gradient interaction, $p = 0.006$). The relationship between stride length and ELI during level walking was stronger for the DP ($r = 0.634$, $p = 0.067$) than for the BP ($r = –0.287$, $p = 0.453$). This would suggest that a shorter stride length is associated with better economy in the DP condition.

Position of centre of mass

The horizontal position of the CoM whilst standing moves anteriorly compared to the unloaded condition in both loading conditions. For the DP the change is 1.97 ± 2.76 cm. This is significantly less than the change of 8.28 ± 1.75 cm associated with the BP condition ($p = 0.0001$). The changes in the vertical direction were not significantly different ($p = 0.154$) with, on average, the CoM associated with the DP moving upwards (2.38 ± 3.55 cm) whilst the CoM associated with the BP moved downwards (0.18 ± 4.26 cm). For both conditions there was a significant relationship between the change in horizontal position of the CoM and ELI ($r = 0.755$, $p = 0.030$ and $r = 0.772$, $p = 0.025$ for DP and BP respectively) suggesting that greater changes in forward lean from the unloaded condition were associated with reduced economy in both loading conditions. Relationships were much weaker for vertical changes in the position of the CoM, $r = –0.077$, $p = 0.857$ and $r = 0.220$, $p = 0.600$ for DP and BP respectively.

Trunk angle

The mean ± s trunk angles associated with each loading condition whilst standing still were 93.5° ± 2.5° unloaded , 89.2° ± 3.1° for the AARN pack and 79.8° ± 4.6° for the traditional pack. These increases in forward lean, 4.4° ± 2.9° and 13.8° ± 4.3° for the DP and BP respectively, were significantly different ($p < 0.0005$).

Figure 3 shows the mean increases in forward lean compared to unloaded walking at the heel strike, mid support and toe off phases of the stride cycle, measured whilst in contact with the force plate. The increase in forward lean caused by the packs is significantly different ($p < 0.0005$) at all three points during the contact phase. The BP induces at least 9 degrees more forward lean than the DP pack at all three points. The increase in forward lean between heel strike and mid support was greater for the DP than the BP (2.27° ± 2.54° vs. 1.83° ± 1.42°). Whilst this difference was not

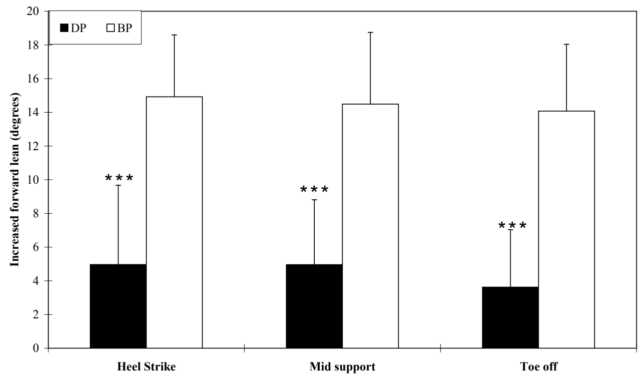

Figure 3. Mean + s increase in forward lean (degrees) above the unloaded condition associated with each pack during walk over the force plate. (*** denotes $p < 0.0005$)

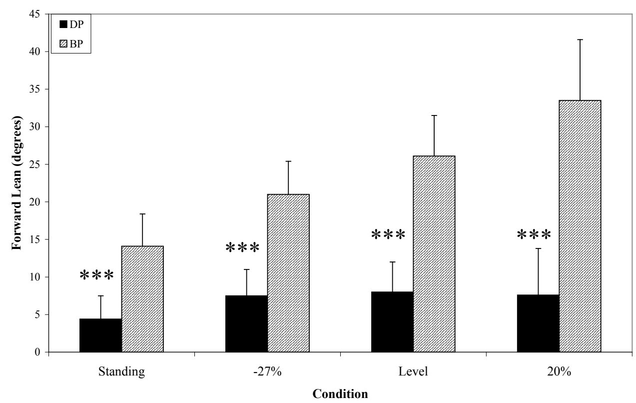

Figure 4. Mean + s increase in forward lean (degrees) above the unloaded condition whilst standing still and walking at various gradients

significant (p = 0.323), the relationship between the increase in forward lean from heel strike to mid support and ELI was significant for the DP (r = –0.867, p = 0.005) but not for the BP (r = 0.454, p = 0.258). This suggests that greater range of motion of the trunk in the early phase of the gait cycle is associated with better economy for the double pack system. In contrast, the differences in trunk angle between the unloaded and BP conditions were strongly related to reduced economy (r = 0.643, p = 0.085 at heel strike, r = 0.670, p = 0.069 at mid support and r = 0.794, p = 0.019 at toe off).

Mean values for increased forward lean whilst walking at the –27%, level and 20% gradients, as well as whilst standing still, are shown in Figure 4.

Considering all three gradients, the BP induced a significantly greater increase in forward lean, on average 13.2°, than the DP (p < 0.0005). The differences between the two packs for increase in forward lean were, on average, 9.1°, 12.7°, and 17.8° for the –27%, level and 20% gradients respectively (p < 0.005). Figure 4 indicates that the extra forward lean induced by the AARN pack remains fairly constant at all gradients whilst the extra forward lean induced by the traditional pack increases as the slope increases.

Relationships between kinetic variable and relative economy

Full results for ground reaction forces have been published elsewhere (Lloyd and Cooke [16]). Considering the DP condition, there were strong relationships between: the magnitude of the first lateral impact peak (r = –0.653, p = 0.079); the difference between the unloaded and loaded first lateral peak force (r = 0.662, p = 0.074); maximum braking force (r = –0.661, p = 0.074); the difference between loaded and unloaded maximum braking force (r = 0.797, p = 0.018) and the times to both the first lateral peak force (r = –0.691, p = 0.058) and the medial peak force (r = –0.798, p = 0.017). For the BP condition the only strong relationships with ELI were in the difference between unloaded and loaded second lateral peak force (r = –0.784, p = 0.021), the time to the same force (r = –0.825, p = 0.012) and the time to maximum braking force (r = –0.624, p = 0.099).

Discussion

Two main approaches have been employed in assessing load carriage economy. The first, and most widely used, is rate of oxygen consumption, usually expressed relative to body mass (e.g. Legg and Mahanty [13], Quesada et al. [17]). The second approach that has been used is the energy cost of walking (Cw) (e.g. Abe et al. [1], Bastien et al. [2]). We would suggest that both of these methods have limitations. The former makes comparison between different studies using different loads and speed of progression very difficult, whilst the latter factors out resting energy expenditure but not the energy expenditure of (unloaded) walking. Both produce values that are difficult to interpret by a non-scientific audience. The ELI, on the other hand, produces a single, dimensionless index, that allows for comparison of different load carriage systems across different studies and also provides a simple to understand ratio that would be useful not only for scientific use but also for manufacturers of load carriage systems, both in development and marketing. From a scientific perspective the ELI has a distinct advantage as it accounts for individual variability in gait. Given that most of the available literature indicates that the cost of carrying extra load is similar to, but slightly greater than, the cost of carrying live mass (e.g. Taylor et al. [23]), then it is likely that the additional element of energy expenditure, above that required simply to support and move the load, is associated with biomechanical changes and that these changes are perturbations from an individual's normal gait pattern. Furthermore, it has been suggested that these normal gait patterns represent the most economical solution for an individual (Martin and Morgan [27]). Thus a measure of loaded economy that accounts for unloaded movement economy has significant utility and merit. In more general terms we would argue that investigations of load carriage, whether they be metabolic, kinematic, kinetic, electromyographic or subjective-perceptual should be referenced to unloaded locomotion.

The ELI values reported here provide further support for the advantage, in terms of physiological cost, associated with double pack systems (e.g. Datta and Ramanathan [12], Legg and Mahanty [13], Coombes and Kingswell [3]). They do, however, indicate that the energy cost of carrying a load in either system is greater than the cost of carrying a unit of body mass.

Previous studies have indicated that back-loading produces only small changes in stride length. Of those that quantified the changes all reported a slight shortening of the stride length relative to unloaded walking or running on the level. Differences have ranged from 1.5% (Thorstensson [28]) to 5% (Cooke et al. [29]). In contrast, Ling et al. [30], Wood and Orloff [31], and Singh and Koh [32] all reported no change in stride length – stride frequency whilst LaFiandra et al. [33] reported a slight lengthening of stride to be associated with two of the three backpacks they studied. Kinoshita

[14] reported no difference in stride length for either a backpack or double pack system. The results of the present study lend support to the view that any changes, at least whilst walking on the level, are small. In contrast to most previous studies, however, the two loaded conditions were associated with a slight increase in stride length during level walking. There was, however, considerable variation between participants with changes in stride length ranging from +12% to –6%. The change in stride length from the unloaded condition increased substantially as the gradient changed from the level in either direction. At the –27% gradient the stride lengths associated with the DP and the BP were, on average, 5.36% and 5.09% shorter than the stride length associated with unloaded walking. At the 20% gradient the reductions were 7.81% and 7.64%.

It has long been established that the stride length–stride frequency combination chosen for a given speed is close to optimum in terms of economy and that relatively large, acute perturbations in stride length–stride frequency result in increases in oxygen consumption (e.g. Cavanagh and Williams [34]). Cooke et al. [29] suggested that a shortening of stride length may be responsible for an improvement in economy with vertical loading as it may lead to a reduction in the vertical oscillation of both the centre of mass and the added load. Given that both increases and decreases in stride length have been associated with increased energy expenditure it might have been expected that the fairly large perturbations evident in the present study, especially at the higher gradients, would have had some effect on economy. There were, however, only two moderate to strong relationships between stride length and ELI. Both were for the DP, suggesting that, on the level, a shorter stride length was associated with improved economy ($r = 0.634$) and that at the 12% downhill gradient, a longer stride length was associated with improved economy ($r = -0.769$). It seems likely then that the perturbations in stride length seen in this, and other studies on load-carriage are insufficient of themselves to explain either the excess energy cost above that required simply to move a unit of live mass (ELI = 1) or to explain differences in economy between load carriage systems.

In terms of the kinematic data presented here it is clear that the single biggest discriminator between the BP and DP conditions is the amount of forward lean provoked by each system. This is consistent with the earlier work of Kinsohita [14]. The magnitude of the forward lean associated with both packs is also consistent with that observed in previous studies. Harman et al. [35] indicated that there was a significant load effect in relation to forward lean associated with walking with a backpack load but no effect of speed. Similarly Polcyn et al. [36], using pooled data from four studies, indicated that 65% of the variance in forward lean could be explained by variance in magnitude of carried load. The load carried in the present study was 25.6 kg, equivalent to, on average, 34.8% bodyweight (BW). The average forward lean whilst walking over the force plate in the BP condition was 12.1°, this is in good agreement with previous studies. Wood and Orloff [31] reported forward lean of 10° whilst carrying a load of 15% BW, whilst Li et al. [37], Hong and Cheung [38] and Singh and Koh [39] reported forward lean of 6.8°, 11.9° and 10.6° respectively when carrying a 20% BW load. LaFiandra et al. [33] reported forward lean of approximately 6° and 12° for loads of approximately 24% and 42% BW, whilst Kinoshita [14] reported forward lean of 11° and 7° for loads of 40% and 20% BW respectively. Data in relation to double pack systems is more scant but Kinoshita [14] reported that the forward lean associated with a double pack system was considerably less than that associated with a double pack. This was not quantified, although inspection of figures showing average trunk inclination across the gait cycle suggest it was of the order of 2.5° which is very similar to the 2.1° of forward lean for the DP observed in this study.

Forward lean during level walking was measured on two occasions in the present study, walking on level ground during the force plate experiment and during the treadmill protocol. The forward lean associated with both loading conditions was greater during the level section of the treadmill protocol than during the force plate experiment. The forward lean associated with the double pack was 2.1° during the force plate protocol and 6.2° during the level section of the treadmill protocol, while for the backpack the increases in forward lean were 12.1° and 18.9° respectively. The forward lean in the unloaded condition remained fairly constant, changing by only 0.4°. There would seem to be a number of possible explanations for this. It may be that the artificial nature of the force plate experiment might have had some effect on posture. Participants were instructed not to look down, had to concentrate on their stride pattern in order to accurately step on the force plate without making adjustments and had to meet the requirements for speed. A number of studies have, however, reported that the kinematics of treadmill and level ground walking are very similar (e.g. Riley et al. [40], Lee and Hidler [41], Parvataneni et al. [42]), even when kinetic or metabolic parameters differ, although none have assessed forward lean. It is likely that a stricture to keep looking ahead will have a greater effect on forward lean than most other kinematic parameters. Alternatively, given that the forward lean for the treadmill protocol was measured at the end of 4 minutes walking, whilst the force plate experiment involved walking only 10 metres, muscular fatigue and/or habituation may have played a part. Two studies have considered this in relation to backpacks (Li et al. [37], Wood and Orloff [31]) and concluded that changes in forward lean across time are minimal. However, both of these studies considered initial measurements after one minute of walking. In the present study a further measure of forward lean was taken, whilst standing still. The forward lean associated with this static condition was 0.8° for the DP and 10.2° for the BP. This finding that static forward lean is smaller than dynamic forward lean, is again consistent with previous research (Singh and Koh [39], Anderson et al. [43]). It has been argued, logically, that, for back-loading in the static condition, the only requirement for stability is that posterior movement of the CoM, caused by the additional load, be countered by the anterior movement of the body's CoM, via increased forward lean, resulting in the system CoM remaining above the base of support (Goh et al. [44]). It has been suggested, however, that this is not a sufficient condition for stability in dynamic conditions (Pai and Patton [45]) and that the horizontal velocity of the CoM needs also to be considered (Hof et al. [46]). Singh and Koh [39] support this theory based on data that suggested that as forward lean increased, walking speed decreased. This is, however, problematic as the causal factor in the speed reduction was additional load, the increased forward lean being a consequence of this. Furthermore, if Hof et al. [46] are correct, it would be anticipated that increasing speed of locomotion would increase forward lean. This is in contrast to the empirical data of Harman et al. [47] and Harman et al. [35] and suggests that, in load carrying, this does not apply.

One striking finding, illustrated in Figure 4, is that the increase in forward lean above the unloaded condition associated with the DP remains fairly constant at all gradients, whilst that for the BP increases with increasing gradient. This observation is consistent with Harman et al. [48] who demonstrated increasing forward lean as the gradient increased from –8% to +8%. The differences in response between the BP and DP are most likely related to changes in the position of the centre of mass. The anterior displacement, relative to the unloaded condition, of the centre of mass whilst standing, was much greater for the BP than for the DP, 8.28 cm as opposed to 1.97 cm. The load itself was discounted in the calculation of the position of the centre of mass. Since addition of mass to the back will result in a posterior displacement of the centre of mass of the whole system, the anterior displacements of the body reported here reflect the compensation necessary for the centre of mass of the whole system to remain over the base of support. This compensation is achieved, for the most part, by increasing the forward lean of the trunk. In addition, and for the same reasons, forward lean increases when walking uphill. Thus walking uphill in the backpack will result in disproportionate increases in forward lean.

One area of particular interest is the range of motion of the trunk through the gait cycle. Despite the much greater magnitude of forward lean associated with the BP than the DP, the change in forward lean during a single foot contact, from heel strike to mid support, was greater in the DP than the BP condition. There is some contrasting data in the literature in relation to this range of motion. Harman et al. [49] suggest that both forward lean and range of motion increase with increasing load, whilst LaFiandra et al. [33] suggest that range of motion decreased with load. Polcyn et al. [36] concluded there was no relationship between trunk range of motion and load (r = 0.33). It would seem likely that as load increases there would be a tendency to resist changes in posture given the energy requirements to accelerate and decelerate the load as it deviates from a neutral position. Harman et al. [25] suggested that a smaller range of motion for the trunk was beneficial as it was closer to unloaded walking. The current data would suggest the opposite. Both the DP and the unloaded conditions were associated with a greater change in forward lean between heel strike and mid support than was the case for the BP condition. This may be particularly important as this change in trunk angle was significantly related to improved economy for the DP condition. Moreover, we have previously argued that it is the momentum associated with this change in trunk ankle that contributed to the requirement for a lower peak propulsive force (Lloyd and Cooke [16]). This may well be one of the energy saving mechanisms that provide advantages for a DP system.

Given that there were strong relationships between increase in forward lean, associated with the horizontal excursion of the CoM, and economy, it is worthwhile examining the physiological cost of this forward lean. Although not directly assessed in the present study, a number of authors have investigated this. Most authors concur that loading the back reduces erector spinae activity at the expense of increased rectus abdominus activity. Carlsöö [50] investigated muscle activity in a variety of loading conditions and found that loading the back relieves the deep muscles of the back, counter-balancing the trunks tendency to fall forward which is normally resisted by the erector spinae muscle, and loads the abdominal muscles. He noted, however, that the activity in the erector spinae increased as forward lean increased. Bobet and Norman [51] found similar decreases in erector spinae activity when the back was loaded but point out that the erector spinae is not the only muscle involved in load carriage and that small changes in the position of the trunk may transfer load from the erector spinae to other muscles. Gordon et al. [52] argued that the increased forward lean associated with loading of the back imposed a greater stress on muscle groups not accustomed to the required work during walking. Specifically forward lean would be resisted by eccentric contracture of the hamstring and semispinalis muscle groups. Motmans et al. [7] considered a number of loading systems and concluded that a doublepack system was the closest to unloaded walking, with very little change in either erector spinae or rectus abdominus activity. This was in contrast to back-loading which caused a significant reduction in erector spinae activity with a concomitant increase in rectus abdominus activity (Motmans et al. [7]); a finding which was consistent with that reported by Al-Khabbaz et al. [53]. Given the trade off in muscular activity associated with forward lean, and the relatively low absolute level of activity in the postural muscles, it would seem unlikely that forward lean is directly responsible for the differences in economy observed. It is likely that the interaction between forward lean and other joint positions, with consequent change in lower limb muscle activity, may be more important and worthy of future comparative study.

It is possible that the effects of any changes in kinematics are not simply additive, but that an interaction exists that may explain differences in economy. Thus, in the present study the combination of changes in stride length and forward lean, and possibly other factors such as the disturbances in the kinematics of the foot (Kinoshita [14]) may result in muscles operating on different parts of their force–velocity and force–length relationships, implying that a greater volume of muscle would be necessary to generate the same force, and changes in mechanical advantage, implying that a greater muscle force will be required to produce the same ground reaction force (Heglund and Taylor [54]).

The finding that, with the double pack, the centre of mass moved upward, by 2.4 cm, relative to the unloaded condition was somewhat unexpected. Further investigation indicated that this may be explained, at least to some extent, by two factors. There appears to be greater knee flexion in the unloaded condition than in the DP condition, the knee to ankle distance was on average 1.2 cm greater in the DP condition, and a raising of the shoulders, the hip to shoulder distance was on average 2.1 cm longer in the DP condition. It is not clear why this might be the case but participant comments indicated that the DP system made them feel as if they were standing up much straighter than normal. Thus the reduced knee flexion and raising of the shoulders may have acted as mechanisms to further reduce static forward lean.

The relationships between kinetic variables and economy are interesting. For the DP condition better economy was associated with a smaller lateral impact peak force and a smaller maximum braking force. In addition, the difference between these forces and the unloaded forces was even more strongly related to economy, with a smaller loaded–unloaded difference being associated with improved economy. This would seem to provide further support for the contention that assessment of load carriage systems should be referenced to unloaded walking and the notion that, for an individual, normal walking gait represents an optimal solution in relation to economy (Martin and Morgan [27]). Reducing these impact peaks may, however, have a further advantage as it has been suggested that it is impact forces that are most closely associated with injury (Polcyn et al. [36]).

Conclusions

The study revealed a number of small, but consistent differences between the double pack and the backpack in kinematic variables. Significant differences included a smaller increase in forward lean and displacement of the centre of mass associated with the double pack. Both of these factors were related to improved economy. These findings can be summarised as showing that the double pack is associated with smaller perturbations from unloaded gait patterns, mainly as a result of significantly less forward lean. These differences suggest that a load carriage system which allows loads to be distributed between both the back and the front of the trunk may be more appropriate for carrying relatively heavy loads than a system which loads the back only, both in terms of injury prevention and economy.

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