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Manuscript Title: The energetic, kinematic and kinetic responses to load carried on the back, on the head and in a doublepack.

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Abstract

The determinants of energy saving phenomena reported for load carried on the head, back and in a doublepack remain unclear. This study compared the energetic, kinematic and kinetic responses to head (H), back (B) and doublepack (DP) loading. Fifteen volunteers walked on an instrumented treadmill at 3 $km \cdot h^{-1}$ with 0, 3, 12 and 20 kg in each loading method. Whole body motion, ground reaction forces (GRF) and metabolic cost were measured. H was less economical than B ($p = 0.014$) and DP ($p = 0.010$). H was also associated with increased step length ($p = 0.045$), decreased cadence ($p = 0.001$), greater trunk ($p < 0.001$) and hip ($p < 0.001$) extension and greater minimum vertical GRF ($p = 0.001$) than B and DP. In conclusion, no energy saving was found for head- or back-loading but economy may be improved with methods that cause smaller perturbations from unloaded walking.

Keywords

Load carriage; Economy; Kinetics; Kinematics

Practitioner summary

Energy saving phenomena are reported for load carried on the head, back and in a doublepack, yet the determinants are unclear. This study shows that smaller perturbations from unloaded to loaded walking are associated with improved economy for certain load carriage conditions, such as the doublepack.

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Introduction

Carrying an external load does not simply change the mass of the carrier; if this were the case then the metabolic energy cost of load carriage would always increase in direct proportion to the mass of the load. Instead, it is generally accepted that carrying a load closer to the body's centre of mass (COM), such as in a backpack, is more economical than carrying the same load further from the body's COM, such as in the hands or on the feet (Soule and Goldman, 1969, Datta and Ramanathan, 1971, Legg and Mahanty, 1985, Abe et al., 2004). While some studies have reported a proportional increase in the energy cost required to carry a load close to the body's COM (Datta and Ramanathan, 1971, Legg and Mahanty, 1985, Huang and Kuo, 2014), energy saving phenomena have been reported for load carried on the head (which places the load in vertical alignment with the body's COM) (Maloiy et al., 1986, Charteris et al., 1989), on the back (Abe et al., 2004) and evenly distributed between the front and back of the torso using a doublepack (Lloyd and Cooke, 2000). Previous work has attempted to identify mechanisms that may contribute to these energy saving phenomena (Jones et al., 1987, Heglund et al., 1995, Abe et al., 2004, Lloyd and Cooke, 2011), yet the determinants remain unclear.

The energy saving phenomenon reported for back-loading by Abe et al. (2004) was for 9 and 12 kg (~10 - 15% body mass) at slow walking speeds (2.4 - 3.6 $km \cdot h^{-1}$). The authors speculated that economy could be improved in these conditions by an increase in what the authors termed 'rotative torque about the lower limb'. This theory implies that a light load carried on the back does not constrain the posture of the trunk to the same extent as a heavy load, allowing for an increased freedom of movement. Theoretically, this would contribute to an increased momentum of the trunk in the sagittal plane, which would increase forward momentum through the gait cycle and reduce the energy required from the lower limb muscles to propel the body forward. Lloyd and Cooke (2000) suggested that a similar mechanism might be responsible for the 5% reduction in $\dot{V}O_2$ they found for 25 kg carried in a doublepack compared to a backpack, when walking at 3 $km \cdot h^{-1}$. However, our research group has shown that trunk motion alone does not appear to explain load carriage economy (Hudson et al., 2018).

In contrast to studies that have found no difference in economy between head-loading and back-loading with inexperienced head-loaders (Datta and Ramanathan, 1971, Lloyd et al., 2010b, Lloyd et al., 2010c), the energy saving phenomena for head-loading reported by Maloiy et al. (1986) suggests that African women (of the Luo and Kikuyu tribes) with head-loading experience can carry up to 20% of their body mass on the head with no additional energy cost above that required for unloaded walking. Furthermore, the authors showed that these women could carry loads above 20% of body mass with a proportional increase in energy cost (e.g. a load of 30% of body mass would result in a 10% increase in energy cost). This remarkable finding was supported by Charteris et al. (1989), who reported that loads of up to 25% of body mass can be carried directly on the head by African (Xhosa) women with several years of head-loading experience before energy cost increased above that required for unloaded walking. Both of these studies had small samples sizes of five (Maloiy et al., 1986) and six (Charteris et al., 1989) participants, and more recently Lloyd et al. (2010c) found that the energy saving phenomenon for head-loading is not a generalizable finding with a larger sample of Xhosa women (*n* = 24). Lloyd et al. (2010c) did report a large level of individual variation in economy for both head- and back-loading, with some individuals being remarkably economical at head-loading, while others were very economical at back-loading. Furthermore, they investigated both experienced (*n* = 13) and inexperienced (*n* = 11) head-loaders and found that 39% of experienced head-loaders had better economy in head-loading than back-loading, while 36% of inexperienced head-loaders exhibited the same tendency. As such, head-loading economy appears to be independent of previous experience but is subject to individual variation. The determinants of this individual variation are yet to be established.

Given the effect of load placement on load carriage economy, knowledge of the kinematics and kinetics associated with head-, back-, and doublepack-loading might help to elucidate the determinants of economy with each method. Few studies have reported the combined kinematic, kinetic and energetic responses to load carriage, and only one study, to our knowledge, has reported them together when comparing different methods of load carriage (Lloyd and Cooke, 2011). This is surprising given that knowledge of the kinetic and kinematic responses to load carriage on the head, on the back and evenly distributed around the torso could help determine the mechanism(s) for the energy saving phenomena that have been reported previously. Lloyd et al. (2010a) conceptualised load carriage economy as the metabolic energy cost of unloaded walking at a given speed, plus the metabolic energy cost required to support and move a given load, whilst accounting for net changes in the energy cost of movement from any changes in the kinematics and kinetics from unloaded to loaded locomotion. The changes in kinematics and kinetics could result from the interaction of the load mass, load carriage method and walking speed. Our research group has shown no difference in economy between head-, back- and doublepack- loading, despite significantly different trunk kinematics between the methods (Hudson et al., 2018). Kinematic and kinetic adaptations to loaded walking could have positive and negative effects on economy. If the positive and negative effects cancel each other out, then the net energy cost of movement from kinematic and kinetic adaptations would be zero. This might explain how others have reported no difference in economy between methods that elicit different walking gait kinematics (such as head-loading compared to back-loading) (Datta and Ramanathan, 1971, Lloyd et al., 2010b, Lloyd et al., 2010c).

The aim of this study was to compare the kinematics, kinetics and economy associated with load carriage on the back, on the head and in a doublepack to establish any energy saving phenomena and associated determinants. It was hypothesised that, (i) a group of inexperienced head-loaders would exhibit a proportional increase in energy expenditure relative to the load mass for all load carriage methods (in line with the previous work of Datta and Ramanathan (1971), Lloyd et al. (2010b) and Lloyd et al. (2010c)), (ii) there would be differences in the kinematics and kinetics of load carriage between methods and, (iii) the most economical participants with each load carriage condition would exhibit less change in posture from unloaded to loaded walking (i.e. smaller changes in kinematics and kinetics from unloaded to loaded walking).

Methods

Participants

Fifteen apparently healthy individuals (10 males, 5 females) volunteered to take part in the study (age 26 ± 3 years, mass 73.6 ± 10.1 kg, stature 1.78 ± 0.07 metres). An *a priori* power calculation performed using G*Power© software determined that a sample size of 15 was required for 80% power and to detect significance ($p < 0.05$), based on an anticipated medium effect size (Partial $\eta^2 = 0.060$; Effect size $f = 0.25$) (Richardson, 2011). Participants were recruited from the student population at KU Leuven, Belgium. All participants had recreational experience of back-loading and no experience of head-loading and doublepack-loading. The study received approval from ethical committees at KU Leuven (Medical Ethics Committee of Universitair Ziekenhuis Leuven) and Leeds Trinity University (School of Social and Health Sciences Ethics Committee).

Experimental design

All trials were conducted in the Movement and Posture Analysis Laboratory at KU Leuven. Participants attended the laboratory on two separate occasions to complete three load carriage conditions in a randomised order. Load carriage conditions differed by method, with load carried on the head (H), on the back (B) or in a doublepack (DP). The order that the load carriage conditions were undertaken was randomised via the picking of marked pieces of paper out of a hat. The first visit was to complete a familiarisation period and one of the randomised load carriage methods. The remaining two randomised load carriage methods were tested in the second visit. The two load carriage methods tested in the second visit were separated by a 10-minute rest period. Two laboratory visits were included for feasibility purposes and were separated by 3-4 days. A potential learning effect across trials was minimised via the randomised order of load carriage conditions and the inclusion of a familiarisation session. Furthermore, all participants had experience of walking on a treadmill. Each load carriage condition involved four-minute periods of walking at 3 $km \cdot h^{-1}$ carrying 0, 3, 12 and 20 kg. This walking speed was selected based on the work of Maloiy et al. (1986), Charteris et al. (1989), Abe et al. (2004) and Lloyd and Cooke (2000) who provided evidence for improved load carriage economy at speeds of ~3 $km \cdot h^{-1}$. Furthermore, this energy saving phenomenon has not been reported at faster walker speeds (Abe et al., 2004). The load masses were selected to represent a light, medium and heavy load based on previous research on non-military populations (Abe et al., 2004, Lloyd et al., 2010b). The order of load mass was consistent for each load carriage condition (lightest to heaviest). As such, any influence of load order was consistent across load carriage methods. Participants were asked to maintain a similar diet and refrain from alcohol consumption and moderate-vigorous exercise in the 24 hours prior to each laboratory visit.

Experimental procedures

Loading methods

The load carriage methods are shown in Figure 1. A commercially available backpack was used for the back-loading method (24L Aeon pack, Lowe Alpine, USA). The doublepack device was also commercially available (Featherlite Freedom, AARN, New Zealand). A plastic bucket with a 20L capacity was used for the head-loading method. A towel was allowed in the head-loading condition to provide a cushion between the head and the bucket. Due to the participants' inexperience at head-loading, the bucket was attached to the ceiling via a rope to ensure that it would not cause harm if dropped (Figure 1, image A). The mass of the load was made up of the load carriage device and rubber weights (to the nearest 100 g).

[Insert Figure 1 about here]

Initial screening and familiarisation

Prior to completing the first trial, all participants completed a health screen questionnaire (to screen for potential contraindications to exercise) and a load carriage history questionnaire. The participants were then familiarised with the experimental protocol and equipment. A typical familiarisation session lasted ~20 minutes and involved walking on an instrumented split-belt motorised treadmill (Force Link, Culemborg, Netherlands) at 3 $\mathrm{km \cdot h^{-1}}$, with 20 kg in each load carriage device. The facemask for the online gas analysis system (Oxycon Mobile, Jaeger) was also fitted, so that participants could become accustomed to it.

Data collection procedures

Each trial began by recording of the participant's body mass using calibrated digital scales (Seca 813, Seca Ltd, UK). Participants were then fitted with retroreflective markers and a face mask and asked to walk unloaded on the treadmill at 3 $\mathrm{km \cdot h^{-1}}$ for four minutes at 0% gradient. This was followed by two-minutes of rest during which the participants were fitted with the appropriate loading device for the trial. The initial load was set at 3 kg. At the end of the rest period, participants recommenced walking with the load at a speed of 3 $\mathrm{km \cdot h^{-1}}$ for a further four minutes. This pattern of work and rest continued with loads of 12 and 20 kg being carried in the subsequent stages.

Metabolic energy cost of walking

Expired gas measurements were made continuously throughout each walking period using a calibrated portable computerised online gas analysis system (Oxycon Mobile, Jaeger). The rate of oxygen consumption ($\dot{V}O_2$) ($\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$) was averaged over the final minute of each walking period and used to calculate relative load carriage economy using the Extra Load Index (ELI) (Lloyd et al., 2010a), which is shown in Equation 1.

$$\mathrm{ELI} = \frac{\mathrm{mlO_{2L}} \cdot \mathrm{kg\ total\ mass^{-1}} \cdot \mathrm{min^{-1}}}{\mathrm{mlO_{2U}} \cdot \mathrm{kg\ body\ mass^{-1}} \cdot \mathrm{min^{-1}}} \qquad \text{Equation 1}$$

Equation 1. $\mathrm{mlO_{2L}}$ and $\mathrm{mlO_{2U}}$ refer to the rate of oxygen consumption when carrying load and when walking unloaded, respectively. An ELI value of 1 indicates that oxygen consumption increased in direct proportion to the mass supported by the muscles. Values <1 or >1 indicate a relatively lower or higher energy cost, respectively.

Kinematic data collection

Whole body motion was measured using a motion capture system (Vicon, Oxford Metrics, UK). Thirteen infra-red cameras (sampling frequency of 100 Hz) were used to capture the trajectories of sixty-five 14 mm spherical reflective markers attached to the participant. The reflective markers were attached bilaterally to anatomical landmarks on the head, upper limbs, trunk, pelvis and lower limbs to define joint centres and track body segments in accordance with the Vicon full body Plug-in Gait model (Vicon, Oxford Metrics, UK). Data were captured for six consecutive strides during the final minute of each walking period. Visual3D (C-Motion, Inc. Germantown, USA) was used to calculate joint angles of the trunk, hip, pelvis, knee and ankle. Marker trajectories were low pass filtered at 6 Hz using a 2nd order Butterworth filter. Gait events of heel-strike and toe-off where automatically identified using the vertical ground reaction force (GRF) data, with detection thresholds set to 20 N. These gait events were used to determine the spatiotemporal variables analysed in this study, which were step length, cadence, step time, double stance time and single stance time. Definitions for these variables are provided in Table 1.

[Insert Table 1 about here]

Kinetic data collection

The split-belt motorised treadmill was instrumented with two force plates that recorded GRF at a sampling frequency of 900 Hz. Kinetic data was filtered at 6 Hz using a low pass 2nd order Butterworth filter, in line with the recommendations of Kristianslund et al. (2012). All force data were normalised to total mass (body mass + load mass, $N \cdot kgTM^{-1}$). Key variables were defined as maximum vertical 1st peak, minimum vertical force during mid-stance, maximum vertical 2nd peak, peak antero-posterior braking force, peak antero-posterior propulsive force, peak medial force and peak lateral force.

Statistical analysis

Means and standard deviations were calculated for the physiological and biomechanical variables for each load method and load mass combination. Normal distribution of data was verified using the Shaprio Wilk test and by visually exploring boxplots. Kinematic and kinetic variables were analysed as the change (Δ) from unloaded to loaded walking by subtracting the value for unloaded walking from that of loaded walking. IBM SPSS (version 22, IBM SPSS Statistics, SPSS inc., Chicago, IL, USA) was used for all statistical analysis. A two-way ANOVA with repeated measures was used to test for significant main effects and interactions between load carriage methods and load masses (method x mass). Post-hoc tests for significant main effects and interactions were conducted using a Bonferroni correction. Effect sizes were calculated using partial eta squared (η^2) and were classified as small (0.010 - 0.059), medium (0.060 - 0.137) and large (>0.138) (Richardson, 2011). Pearson's product moment correlation coefficients were calculated to assess relationships between ELI and the change in kinematic and kinetic variables from unloaded walking. Correlation coefficients were interpreted using intervals of negligible correlation (0.0-0.09), weak correlation (0.10-0.39), moderate correlation (0.40-0.69), strong correlation (0.70-0.89) and very strong correlation (>0.90) (Schober et al., 2018).

Results

Load carriage economy

There was no significant difference in $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) between trial conditions when walking unloaded ($p = 0.390$). The Δ $\dot{V}O_2$ from unloaded to loaded walking was significantly different between load carriage methods (main effect of load method $p = 0.001$; $\eta^2 = 0.440$) and load masses (main effect of load mass, $p = 0.001$; $\eta^2 = 0.857$) (Figure 2). Head-loading produced the greatest Δ $\dot{V}O_2$ from unloaded to loaded walking with all load mass conditions. The largest Δ $\dot{V}O_2$ between loading methods occurred with the heaviest load (20 kg), with an increase in $\dot{V}O_2$ from unloaded walking of 4.14 ± 2.10 ml·kg^{-1}·min^{-1}, 2.42 ± 1.14 ml·kg^{-1}·min^{-1} and 1.91 ± 0.93 ml·kg^{-1}·min^{-1} for Head, Back and Doublepack, respectively. Post-hoc analysis showed that $\dot{V}O_2$ increased significantly with each increase in load mass ($p \leq 0.05$) and $\dot{V}O_2$ was significantly greater for H compared to the two trunk-loading methods ($p \leq 0.05$).

ELI values were significantly different between load carriage methods (main effect of load method, $p = 0.002$; $\eta^2 = 0.423$). Post hoc analysis showed that ELI values were significantly greater for H compared to B ($p = 0.014$) and DP ($p = 0.010$) methods (Figure 2). The largest difference in ELI values between methods was with 20 kg (1.10 ± 0.15, 0.98 ± 0.09 and 0.94 ± 0.08 for H, B and DP, respectively). There was no difference in ELI between B and DP ($p = 1.000$). There was also no significant difference in ELI between load masses (main effect of load carriage mass, $p = 0.410$; $\eta^2 = 0.054$), but there was a significant method x mass interaction ($p = 0.030$; $\eta^2 = 0.211$) with ELI increasing as load mass increased for H but decreasing as load mass increased for DP.

[Insert Figure 2 about here]

Kinematic data

A significant large main effect of load carriage method was observed for the Δ step length ($p = 0.045$, $\eta^2 = 0.198$), Δ cadence ($p = 0.001$, $\eta^2 = 0.391$), Δ step time ($p = 0.013$, $\eta^2 = 0.268$) and Δ single stance time ($p = 0.010$, $\eta^2 = 0.283$) from unloaded to loaded walking (Table 2). There were also significant large method x mass interaction effects for Δ step length ($p = 0.008$, $\eta^2 = 0.216$) and Δ cadence ($p = 0.001$, $\eta^2 = 0.292$). Specifically, cadence was significantly lower for B compared to H ($p = 0.010$) and DP ($p = 0.032$), with Δ cadence decreasing as the mass of the load increased from unloaded walking for B (Δ cadence of -0.01 ± 0.03, -0.03 ± 0.04 and -0.03 ± 0.06 steps$_{\cdot}$s^{-1} for 3, 12 and 20 kg, respectively) and increasing from unloaded for H (Δ cadence of 0.02 ± 0.04, 0.03 ± 0.06 and 0.06 ± 0.08 steps$_{\cdot}$s^{-1} for 3, 12 and 20 kg, respectively). The Δ cadence from unloaded to loaded walking for DP was similar across load mass (0.01 ± 0.03, 0.01 ± 0.03 and 0.00 ± 0.04 steps$_{\cdot}$s^{-1} for 3, 12 and 20 kg, respectively).

There was a tendency for step time to decrease from unloaded to loaded walking for H compared to B (-0.01 ± 0.02 s vs. 0.01 ± 0.02 s, $p = 0.058$). The Δ single stance time from unloaded to loaded walking decreased significantly for H compared to B (-0.02 ± 0.02 s vs. 0.00 ± 0.02 s, $p = 0.026$) and there was also a tendency for reduced single stance time for H compared to DP (DP = -0.01 ± 0.02 s, $p = 0.070$). There was no significant difference between loading methods for single stance time (H = 70 ± 2%, B = 70 ± 2% DP = 69 ± 3%, $p = 0.155$, $\eta^2 = 0.125$) and double stance time (H = 30 ± 2%, B = 30 ± 2% DP = 31 ± 3%, $p = 0.155$, $\eta^2 = 0.125$) when considered as a percentage of step time.

There was a significant main effect of load mass for single stance time ($p < 0.001$, $\eta^2 = 0.458$) and double stance time ($p < 0.001$, $\eta^2 = 0.808$). Post hoc analysis showed that double stance time significantly increased from unloaded to loaded walking with each increase in load mass ($p < 0.05$). Single stance time significantly decreased from unloaded to loaded walking by -0.01 s with 12 kg compared to 3 kg ($p = 0.049$) and by -0.02 s with 20 kg compared to 3 kg ($p = 0.002$).

[Insert Table 2 about here]

Figure 3 illustrates the sagittal plane joint angles over the gait cycle for each load carriage method. There was a significant large main effect of load carriage method for the Δ peak trunk extension ($p < 0.001$, $\eta^2 = 0.861$) Δ peak trunk flexion ($p < 0.001$, $\eta^2 = 0.894$) and Δ peak trunk ROM ($p = 0.003$, $\eta^2 = 0.347$). There were also significant large method x mass interactions for the Δ peak trunk flexion angle ($p = 0.001$, $\eta^2 = 894$) and the Δ peak trunk extension angle ($p = 0.001$, $\eta^2 = 861$) from unloaded to loaded walking. Specifically, H was associated with a more upright posture compared to B and DP, with significantly less peak trunk flexion from unloaded to loaded walking for H (-7.42 ± 3.39°) compared to B (3.76 ± 3.19°, $p < 0.001$) and DP (1.93 ± 1.47°, $p < 0.001$). Furthermore, B was associated with a larger Δ peak trunk flexion from unloaded to loaded walking compared to DP ($p = 0.003$).

There was a significant large main effect of load carriage method for the Δ trunk axial rotation ($p < 0.001$, $\eta^2 = 0.621$) and Δ pelvic axial rotation ($p = 0.001$, $\eta^2 = 0.373$) from unloaded to loaded walking (Figure 4). Specifically, there was a significant decrease in trunk axial rotation for H (-4.14 ± 2.61°) compared to B (-1.37 ± 1.82°, $p = 0.001$) and DP (-1.00 ± 2.07°, $p < 0.001$). Pelvic rotation was closer to that of unloaded walking for H (0.10 ± 1.95°) compared to B (-1.58 ± 1.57°) and DP (-1.67 ± 1.54°) which both had significantly decreased pelvic rotation from unloaded to loaded walking (H vs. B, $p = 0.014$; H vs. DP, $p = 0.015$).

[Insert Figure 3 about here]

[Insert Figure 4 about here]

Kinetic data

Significant large main effects of load method were observed for the Δ minimum vertical force (p = 0.001, η^2 = 0.469) and the Δ 2nd peak component of vertical force (p = 0.003, η^2 = 0.339) during unloaded walking (Table 3). For the Δ minimum vertical force from unloaded to loaded walking, post hoc analysis revealed significantly greater minimum force for H (8.99 ± 0.17 $N \cdot kgTM^{-1}$) compared to B (8.88 ± 0.17 $N \cdot kgTM^{-1}$) (p = 0.035) and DP (8.83 ± 0.19 $N \cdot kgTM^{-1}$) (p = 0.002). The Δ 2nd peak component of vertical force was significantly lower for H compared to DP (p = 0.011) and approaching significantly lower than B (p = 0.062).

[Insert Table 3 about here]

Significant relationships between ELI and biomechanical data

For DP with 20 kg, there was a moderate positive correlation between ELI and the Δ peak trunk angle extension (r = 0.535, r^2 = 28.62%, p = 0.040) and Δ peak trunk angle flexion (r = 0.578, r^2 = 33.41%, p = 0.024) from unloaded to loaded walking (Figure 5). This indicates that improved economy, shown by lower ELI values, is associated with smaller changes in peak trunk angles from unloaded to loaded walking. However, there was no significant relationship shown for the 3 kg or 12 kg loading conditions between ELI and the Δ peak trunk angle extension (r = -0.082, p = 0.771 and r = 0.071, p = 0.801, respectively) and ELI and the Δ peak trunk angle flexion (r = -0.132, p = 0.640 and r = -0.115, p = 0.684, respectively), which suggests these relationships are not generalisable across all loads. There was also a moderate negative relationship for ELI and the Δ 2nd peak vertical force relative to total mass ($N \cdot kgTM^{-1}$) from unloaded to loaded walking with 20 kg (r = -0.603, r^2 = 36.36%, p = 0.017) for DP with 20kg.

[Insert Figure 5 about here]

For H with 12 kg, ELI was negatively correlated with Δ step length (r = -0.650, r^2 = 42.25%, p = 0.009) and Δ double stance time (r = -0.651, r^2 = 42.38%, p = 0.009) from unloaded to loaded walking. There was also a moderate positive correlation for the Δ cadence from unloaded to loaded walking with 12 kg carried on the head (r = 0.574, r^2 = 32.94%, p = 0.023) (Figure 6). However, there was no significant relationship shown for the 3 kg or 20 kg loading conditions between ELI and Δ step length (r = -0.335, p = 0.222 and r = -0.213, p = 0.446, respectively), ELI and Δ cadence (r = 0.263, p = 0.343 and r = 0.149, p = 0.569, respectively) or ELI and Δ double stance time (r = -0.479, p = 0.071 and r = 0.079, p = 0.781, respectively).

[Insert Figure 6 about here]

For B, there were moderate positive correlations between ELI and the Δ double stance time from unloaded to loaded walking with 12 kg (r = 0.648, r^2 = 41.99% p = 0.009) and 20 kg (r = 0.644, r^2 = 41.47% p = 0.010). There was also a moderate positive correlation between ELI and the Δ in medial force relative to total mass ($N \cdot kgTM^{-1}$) from unloaded to loaded walking for B with 12 kg (r = 0.531, r^2 = 28.19%, p = 0.042).

Discussion

The aim of this study was to compare the energetic, kinematic and kinetic responses to load carried on the head, back and in a doublepack, in order to establish any energy saving phenomena and associated determinants. The main findings of this research are: (1) Carrying load on the head was less economical than using a backpack or a doublepack for a group of inexperienced head-loaders; (2) There was significantly greater trunk and hip extension for head-loading, along with an increased step cadence and a concomitant decrease in step length compared to the two trunk loading methods; (3) There was a smaller minimum vertical force and greater 2nd peak for vertical force for head loading compared to the two trunk loading methods; (4) Improved load carriage economy (evident from lower ELI values) was significantly correlated with smaller unloaded to loaded changes in the sagittal plane peak trunk angles for the doublepack method with 20 kg; (5) Improved economy was also significantly correlated with smaller unloaded to loaded changes in step length and cadence, with an accompanying increase in double stance time for head-loading with 12 kg.

Head-loading was not an economical method of load carriage compared to the two trunk loading methods. This contrasts with the findings of Datta and Ramanathan (1971), Maloiy et al. (1986) and Lloyd et al. (2010b), who all reported no difference between head- and back-loading economy for inexperienced head-loaders. Although our group data for head-loading economy suggest that inexperienced individuals are not economical with this method, Lloyd et al. (2010c) suggested that head-loading economy is independent of experience, reporting that both experienced and inexperienced head-loaders can be very economical (ELI values of less than 0.9) and very uneconomical (ELI values of up to 1.4) in head-loading. Based on the individual variation in head-loading economy shown by Lloyd et al. (2010c) and the small number of inexperienced head-loaders included in the studies by Datta and Ramanathan (1971) (*n* = 7), Maloiy et al. (1986) (*n* = 3) and Lloyd et al. (2010b) (*n* = 9), it is possible that the poor head-loading economy in the present study compared to previous research was, in part, a result of a sub-set of participants being very uneconomical when head-loading (five participants had ELI values of >1.20). Furthermore, no participants had ELI values of that magnitude with the other methods, with only two participants having an ELI >1.10 in the back and doublepack loading methods. Interestingly, from the data provided by Lloyd et al. (2010b) we calculated ELI values for head-loading of 1.07, 1.10 and 1.15 when carrying 10% (6.7 kg), 20% (13.5 kg) and 30% (20.2 kg) of body mass, respectively. As such, the head-loading economy reported by Lloyd et al. (2010b), for nine female participants from the British Territorial Army (no head-loading experience), are similar to the ELI values for head-loading found in the present study (1.06 ± 0.09, 1.07 ± 0.11 and 1.10 ± 0.15, for 3, 12 and 20 kg, respectively).

The difference in trunk posture between the head- and back-loading methods was expected, given that backpacks shift the COM of the combined body and backpack (combined system) in the posterior direction and forward lean occurs to counter the posterior shift and keep the COM of the combined system over the base of support (Kinoshita, 1985, Martin and Nelson, 1986, Goh et al., 1998, Harman et al., 2000). In contrast, head-loading requires an upright posture to balance load directly on the head. Despite the differences in sagittal plane trunk motion between methods, we have previously shown that this, alone, does not determine differences in economy between load carriage methods (Hudson et al., 2018). The reduction in trunk axial rotation for head-loading compared to the two trunk loading methods is also likely to be a consequence of the need to balance the load on the head. The decrease in trunk rotation for head-loading was accompanied by increased pelvic rotation compared to the two trunk loading methods. LaFiandra et al. (2003b) has previously suggested that the coordination between the relative rotations of the torso and pelvis combine to reduce the net angular momentum of the body. This would explain the pattern of response observed between the axial rotation of the pelvis and trunk in the present study.

LaFiandra et al. (2003b) also suggested that a key factor in decreased stride length during load carriage is a decrease in pelvic rotation, with an increase in step cadence to compensate when walking at a given speed. However, in the present study head-loading was associated with a decrease in step length and an increase in cadence compared to the other methods, despite a greater amount of pelvic rotation. Step length and the associated trajectory of the whole body centre of mass is determined by more than just pelvic rotation (Inman and Eberhart, 1953, Kerrigan et al., 2001) and other factors that influence step length include angles of the hip, knee and ankle (Schulz et al., 2008). As such, the decreased step length for head-loading compared to the two trunk loading methods, despite greater pelvic rotation, may be due to the larger hip extension and reduced hip flexion for head-loading. Despite head-loading being less economical than the other methods, there was a significant relationship between improved head-loading economy and increased double stance time from unloaded walking (Figure 6) when carrying 12 kg. It's possible that participants that had longer durations of double stance had improved stability, which has been linked to an improved economy for unloaded walking (Kuo and Donelan, 2010). However, the lack of significant relationships between ELI and the Δ double stance time with the 3 kg and 20 kg loads suggest that this is not generalisable relationship across load masses.

The doublepack method was associated with a 4% decrease in $\dot{V}O_2$ compared to back-loading with 20 kg. This is similar to the 6% decrease reported by Lloyd and Cooke (2000) and the 6.4% decrease reported by Legg and Mahanty (1985) for heavy load (> 20 kg) carried in a doublepack compared to a backpack. Figure 3 shows that the joint angle movements of the trunk and hip were closer to those of unloaded walking for the doublepack method compared to back-loading. We also found significant positive relationships between ELI and the change in peak trunk flexion and peak trunk extension angles from unloaded to loaded walking when carrying 20 kg in a doublepack. This is in agreement with Lloyd and Cooke (2011) suggested that a greater freedom of movement of the trunk when carrying heavy load in a doublepack (compared to a backpack) might be responsible for an improved load carriage economy for that method. However, like the difference in relationships between ELI and double stance time across load masses in the head-loading method, the lack of significant relationships between ELI and peak trunk angles with the 3 kg and 12 kg loads in the doublepack suggest that these are not generalisable relationships across load masses.

The present study did not confirm the energy saving phenomenon reported by Abe et al. (2004) for moderate loads of 9 – 12 kg (10-15% of body mass) carried on the back. The 12 kg load was equivalent to, on average, 17% of body mass and as such it could be that the 12 kg load in the present study was too heavy to show this energy saving phenomenon. However, on closer examination of individual data, the 12 kg condition was equivalent to between 10-15% body mass for 6 participants who did not exhibit an energy saving phenomenon, with an average ELI value of 1.01 ± 0.07 for the 12 kg back-loading condition. A more likely reason for not observing an energy saving phenomena for this load carriage condition is because of a lack of difference in the trunk range of motion between the load masses. The trunk was not less constrained in the sagittal plane with 12 kg compared to the heavier load and would not have benefited from an increased forward momentum through the gait cycle.

The only significant difference in ground reaction forces between methods was a greater minimum vertical force and lower 2nd vertical peak force for head-loading compared to the other methods. While there is a paucity of research comparing the kinetics of different load carriage methods, our findings are consistent with those of Lloyd et al. (2011) who reported the same differences in vertical force between head-loading and back-loading in a group of experienced head-loaders. Birrell and Haslam (2008) suggested that the minimum vertical force occurs when the COM is at its highest point in the gait cycle and showed that raising the COM by carrying a wooden rifle increased the minimum vertical force. Head-loading will raise the COM of the system compared to both back- and doublepack-loading due to the position of the load and the use of the arms to support the load on the head.

The smaller 2nd peak of vertical force for head-loading compared to the two trunk loading methods in the present study was also reported by Lloyd et al. (2011). There is little consistency in the literature in relation to differences in the 2nd peak of vertical force between trunk-loading methods. Birrell and Haslam (2010) and Hsiang and Chang (2002) reported a smaller 2nd peak of vertical force for back-loading compared to load more evenly distributed around the trunk. However, similar to our results, Kinoshita (1985) and LaFiandra et al. (2003a) found no difference in the 2nd peak of vertical force between different methods of trunk-loading. Increased forward lean and increased stride length have been suggested as mechanisms for smaller 2nd peak vertical force between different methods of trunk loading (Kinoshita, 1985, Birrell and Haslam, 2010). However, in the present study neither increased forward lean or increased stride length explain a smaller 2nd peak of vertical force for head-loading.

The single controlled walking speed could be considered a limitation to this study. Walking speed was controlled at 3 $km \cdot h^{-1}$ for comparisons with previous research that demonstrated energy saving phenomena when carrying load at the same speed (Maloiy et al., 1986, Abe et al., 2004, Lloyd and Cooke, 2000). As such, the conclusions drawn from this research cannot be generalised to other walking speeds. While load carriage methods that cause smaller perturbations from unloaded walking appear to improve load carriage economy, further research is warranted to assess the determinants of improved economy for certain populations, such as those in the military and emergency services, who are regularly required to walk at speeds in excess of 5 $km \cdot h^{-1}$ when carrying load (Knapik et al., 2012). Furthermore, military populations are regularly required to carry loads in excess of 20 kg for prolonged periods of time (Knapik et al., 2012) and future research would benefit from assessing mechanisms for an improved economy under these conditions. Another limitation of this study could be the fixed order that the loads were carried. Any influence of load order was consistent across load carriage methods, and the order from lightest to heaviest is in line with previous research comparing multiple loading methods (Abe et al., 2004, Kinoshita, 1985, Lloyd et al., 2010b, Lloyd et al., 2010c). However, we acknowledge that some residual fatigue may have been apparent with the heavier loads as a consequence of the fixed order.

Conclusion

Inexperienced head-loaders were less economical when carrying a load on the head compared to on the back or in a doublepack. Head-loading also resulted in significantly greater change in trunk angle and hip angle (magnitude and direction), step patterns, minimum vertical force and 2nd peak vertical force from unloaded to loaded walking compared to the two trunk loading methods. There was, however, a smaller change in pelvic rotation from unloaded to loaded walking for head-loading compared to the other loading methods, which is likely to be a consequence of decreased axial rotation of the trunk in order to balance the load on the head. Furthermore, the significant correlations between ELI and peak trunk flexion and peak trunk extension angles with 20 kg carried in a doublepack indicate that a better load carriage economy is associated with peak trunk angles closer to those of unloaded walking. It appears that load carriage methods that cause greater perturbations across a range of variables from the unloaded walking gait can be less economical.

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Figures

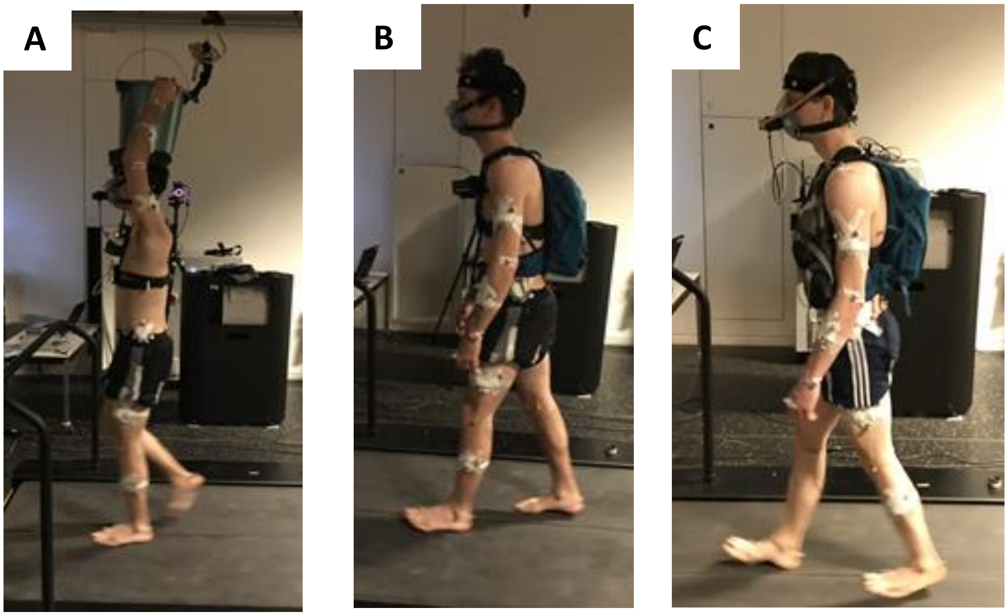

Figure 1. Sagittal plane images of the (A) head, (B) back and (C) doublepack load carriage methods.

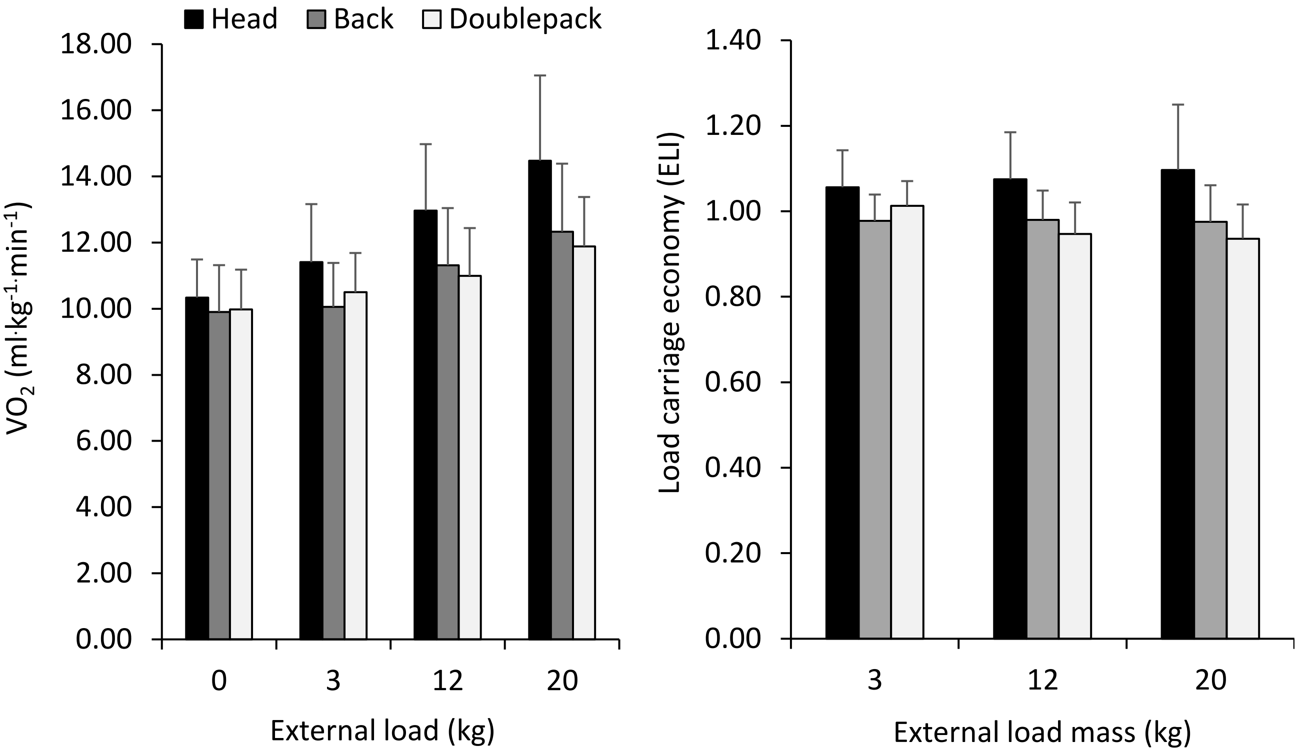

Figure 2. Mean ± SD $\dot{V}O_2$ (left graph) and Extra Load Index (ELI) values (right graph) for each load carriage method and load mass.

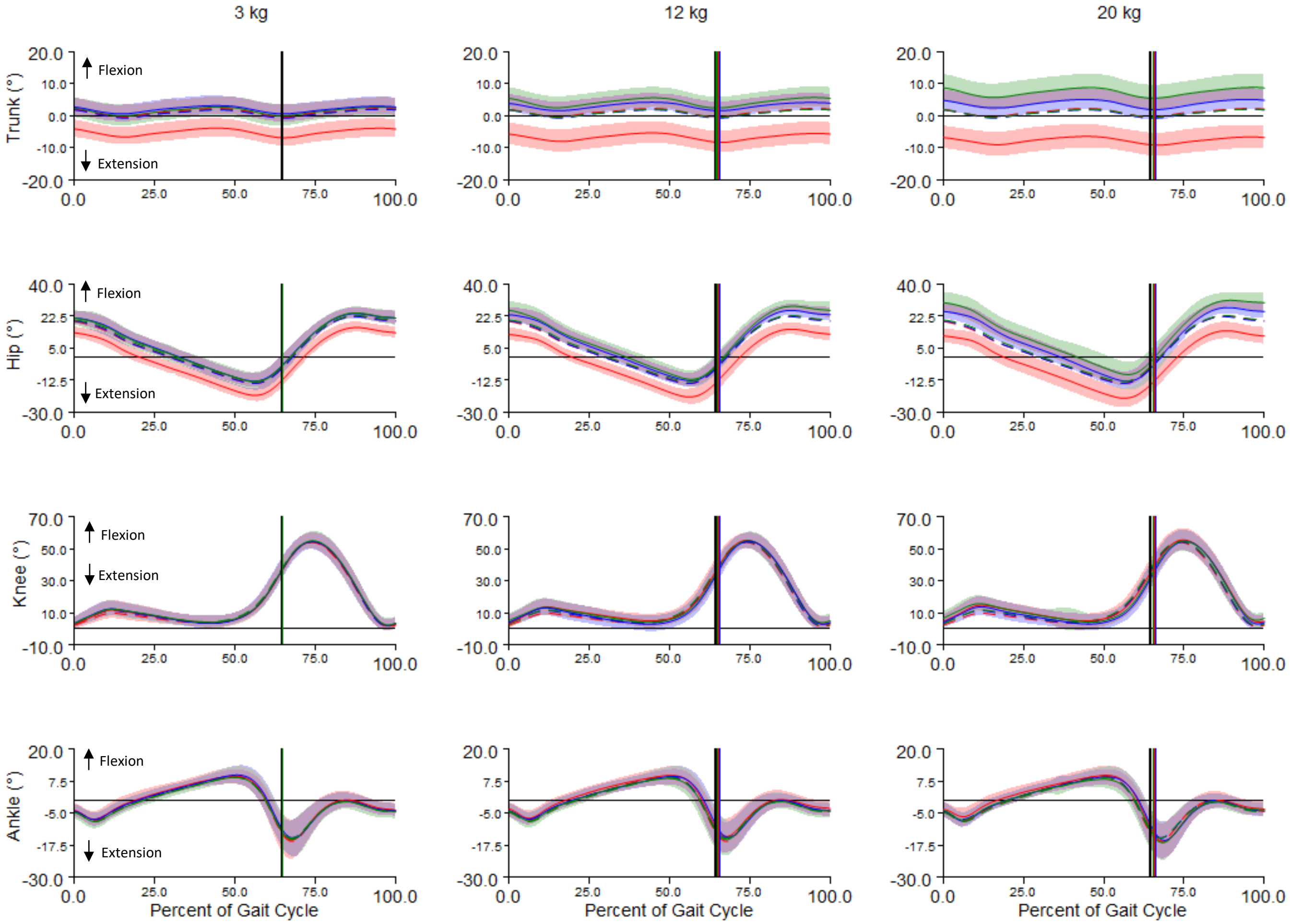

Figure 3. Trunk, hip, knee and ankle sagittal plane kinematics while carrying 3, 12 and 20 kg. Red lines represent the head-loading method, green lines represent the back-loading method and blue lines represent the doublepack method. The shaded areas represent standard deviations. Unloaded walking kinematics for each method are included as dashed lines in each figure. Vertical lines indicate the end of the stance phase.

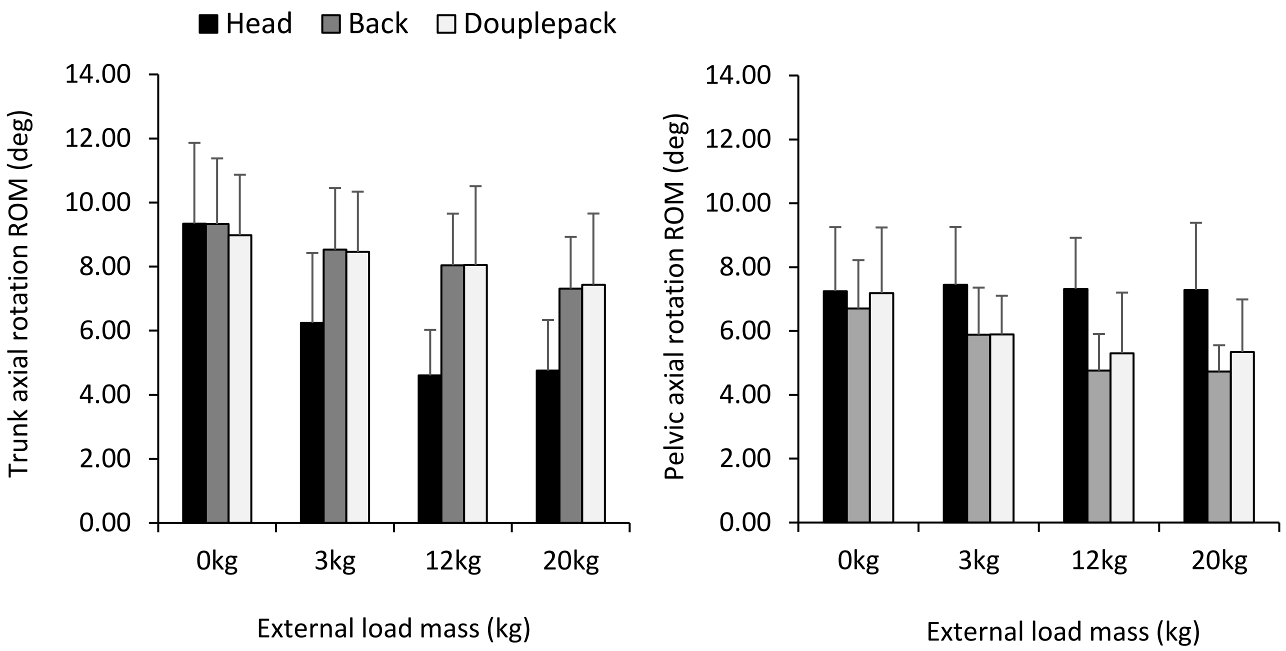

Figure 4. Mean ± SD trunk and pelvic axial rotation (degrees) for each load carriage condition.

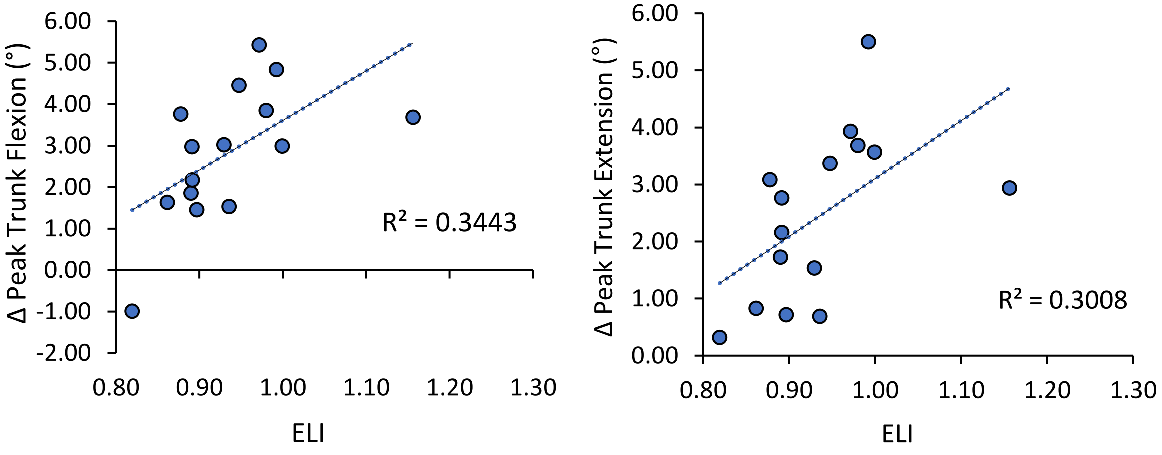

Figure 5. Correlations between ELI and the change in peak trunk flexion and peak trunk extension from unloaded to loaded walking in the DP 20 kg condition.

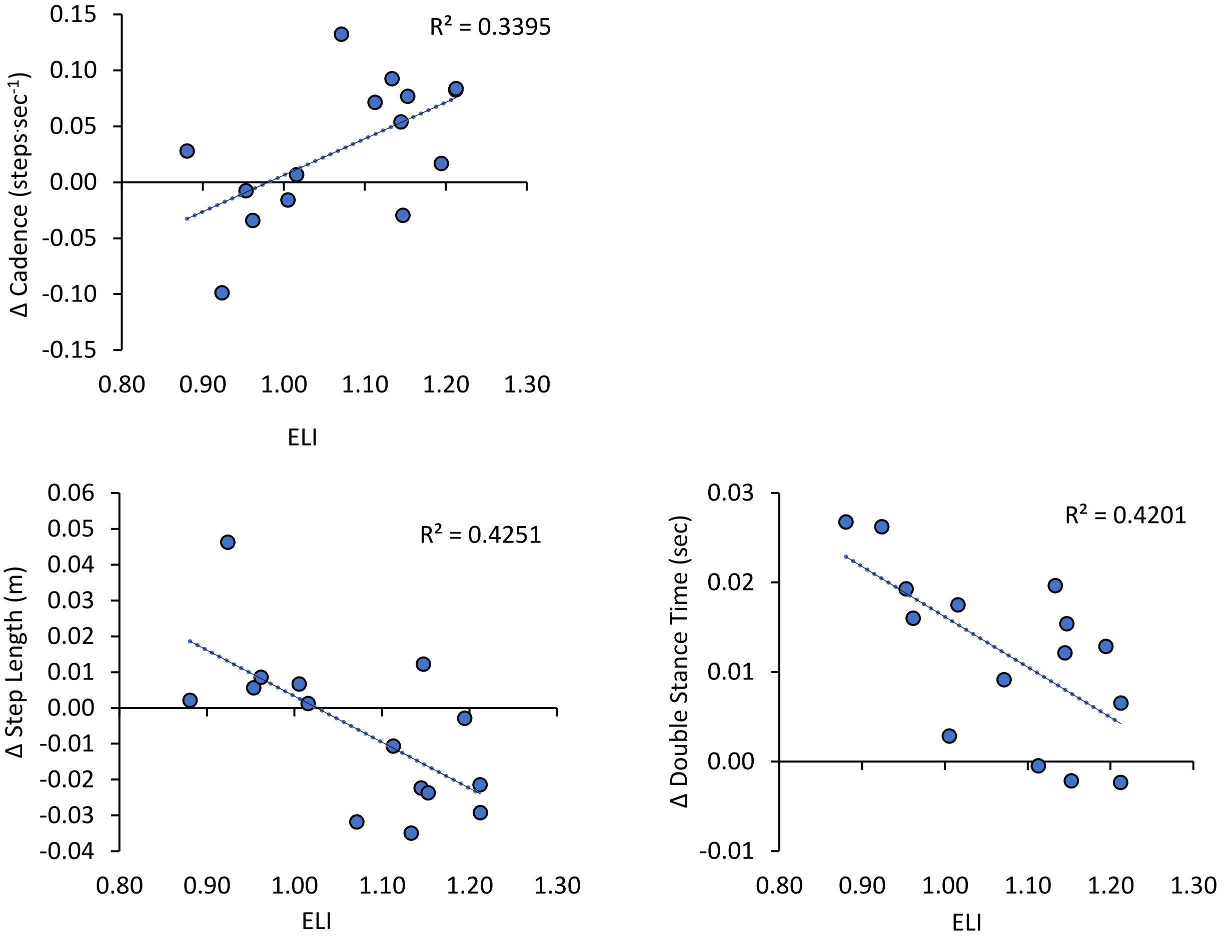

Figure 6. Correlations between ELI and the change in cadence, step length and double stance time from unloaded to loaded walking in the H 12 kg condition.

Tables

Table 1. Definitions for the measured spatiotemporal variables

Spatiotemporal variable	Definition
Step length	Distance between the contralateral foot at the previous contralateral heel strike to the ipsilateral foot at the ipsilateral heel strike. This is calculated as the distance in the walking path direction.
Cadence	The rate at which a person walks, measured in steps per second.
Step time	Time take from one heel-strike to the contralateral heel-strike, measured in seconds.
Double stance time	The time spent with both feet in contact with the ground during a step, measured in seconds
Single stance time	The time spent with a single foot in contact with the ground during a step, measured in seconds**.**

Table 2. Mean ± SD magnitudes for spatiotemporal gait parameters unloaded walking and each load carriage condition. Significance values are for the change from unloaded walking for each variable.

Spatiotemporal variables	0 kg			3 kg			12 kg			20 kg			*p* - value	
	H	B	DP	H	B	DP	H	B	DP	H	B	DP	Method	Mass
Step length (metres)	0.54 ± 0.03	0.54 ± 0.03	0.53 ± 0.03	0.53 ± 0.03	0.53 ± 0.03	0.53 ± 0.03	0.53 ± 0.03	0.54 ± 0.04	0.53 ± 0.03	0.52 ± 0.04	0.55 ± 0.04	0.54 ± 0.03	**0.045**	0.374
Cadence (steps·s^{-1})	1.56 ± 0.08	1.56 ± 0.09	1.56 ± 0.08	1.58 ± 0.09	1.56 ± 0.09	1.57 ± 0.08	1.59 ± 0.10	1.54 ± 0.09	1.57 ± 0.09	1.61 ± 0.12	1.53 ± 0.10	1.56 ± 0.07	**0.001**	0.729
Step time (s)	0.64 ± 0.03	0.64 ± 0.03	0.64 ± 0.03	0.64 ± 0.04	0.64 ± 0.04	0.64 ± 0.03	0.63 ± 0.04	0.65 ± 0.04	0.64 ± 0.04	0.62 ± 0.05	0.65 ± 0.04	0.64 ± 0.04	**0.013**	0.591
Single stance time (s)	0.46 ± 0.03	0.45 ± 0.03	0.45 ± 0.03	0.45 ± 0.03	0.46 ± 0.03	0.45 ± 0.03	0.44 ± 0.03	0.46 ± 0.03	0.44 ± 0.03	0.43 ± 0.03	0.45 ± 0.03	0.44 ± 0.02	**0.010**	**< 0.001**
Double stance time (s)	0.18 ± 0.02	0.19 ± 0.02	0.19 ± 0.02	0.19 ± 0.01	0.19 ± 0.02	0.19 ± 0.02	0.20 ± 0.02	0.20 ± 0.02	0.20 ± 0.02	0.20 ± 0.02	0.20 ± 0.01	0.21 ± 0.02	0.743	**< 0.001**

H = Head, B = Back, DP = Doublepack

Table 3. Mean ± SD magnitudes for ground reaction forces for unloaded walking and each load carriage condition. Significance values are for the change from unloaded walking for each variable.

Peak kinetic variables	0kg			3kg			12kg			20kg			*p* - value	
	H	B	DP	H	B	DP	H	B	DP	H	B	DP	Method	Mass
Vertical GRF														
1st Peak (N·kgTM^{-1})	10.1 ± 0.2	10.1 ± 0.2	10.1 ± 0.2	10.1 ± 0.2	10.1 ± 0.2	10.0 ± 0.3	10.0 ± 0.3	10.1 ± 0.3	9.9 ± 0.2	9.9 ± 0.3	9.9 ± 0.3	9.9 ± 0.3	0.512	**< 0.001**
Minimum (N·kgTM^{-1})	8,9 ± 0.2	8.9 ± 0.1	8.9 ± 0.2	9.0 ± 0.1	8.9 ± 0.2	8.8 ± 0.2	9.1 ± 0.2	8.9 ± 0.2	8.8 ± 0.2	9.0 ± 0.1	8.9 ± 0.2	8.9 ± 0.2	**0.001**	0.196
2nd Peak (N·kgTM^{-1})	10.5 ± 0.3	10.5 ± 0.3	10.5 ± 0.3	10.3 ± 0.3	10.6 ± 0.2	10.5 ± 0.3	10.3 ± 0.3	10.5 ± 0.2	10.4 ± 0.3	10.1 ± 0.3	10.4 ± 0.2	10.4 ± 0.2	**0.003**	**0.001**
AP GRF														
Braking (N·kgTM^{-1})	1.0 ± 0.2	1.0 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.1	1.1 ± 0.2	1.1 ± 0.2	0.253	**0.008**
Propulsive (N·kgTM^{-1})	-1.3 ± 0.2	-1.4 ± 0.2	-1.4 ± 0.2	-1.3 ± 0.2	-1.4 ± 0.1	-1.4 ± 0.2	-1.3 ± 0.2	-1.4 ± 0.2	-1.4 ± 0.2	-1.3 ± 0.1	-1.4 ± 0.2	-1.4 ± 0.2	0.147	0.645
ML GRF														
Medial (N·kgTM^{-1})	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.135	0.357
Lateral (N·kgTM^{-1})	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.649	**0.004**

H = Head, B = Back, DP = Doublepack, GRF = Ground reaction forces, AP = Anteroposterior, ML = Mediolateral.