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Title: Inter-individual variability in load carriage economy and comparisons between different load conditions.

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ABSTRACT

Equivocal findings exist for the economy associated with load carried close to the body’s centre of mass. Individual variation could explain some of the equivocal findings. This research aimed to examine the extent of individual variation in loaded walking economy.

Eighteen females carried load on the back, head and split between the front and back. Individual variation in relative load carriage economy (ELI) was primarily assessed using standard deviation, coefficients of variation (CV) and intraclass correlation coefficients (ICC).

There was large inter-individual variation in ELI values with highest mean CV’s of 16%, 12% and 10% for head-, back- and combined front and back-loading. Mean ELI values were not significantly different between methods.

The large amount of individual variation found here suggests future load carriage research should account for individual variation, particularly when considering sample size and when making inferences on the economy associated with different types of load carriage using group mean data.

Key words: load carriage, economy, physiology, individual variation, physical work

1. INTRODUCTION

The necessity to manually carry load remains prevalent in the military, in the emergency services, for school children, and for many people living in developing countries. Consequently, there has been much attention on the load carriage economy associated with different methods. The early studies of Soule and Goldman (1969), Datta and Ramanthan (1971) and Legg (1985) all concluded that, in order to reduce metabolic energy expenditure, the optimum method of load carriage should bring the centre of mass (COM) of the load as close as possible to the COM of the body. The metabolic energy cost required to transport a load placed close to the COM of the body (e.g. in a rucksack) tends to rise proportionally to the additional mass being carried (Taylor *et al.* 1980; Huang and Kuo, 2014). Yet, energy saving phenomena have been reported with loads carried on the head (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 (back/front-loading) (Lloyd and Cooke, 2000). Despite attempts to identify the potential mechanisms that may contribute to the energy saving phenomena reported in these methods of loading (Jones *et al.*, 1987; Heglund *et al.*, 1995; Abe *et al.*, 2004; Lloyd and Cooke, 2011), the determinants remain unclear.

Our research group has identified a considerable amount of inter- individual variation in loaded walking economy with loads of 10-25% body mass carried on the back and head (Lloyd *et al.*, 2010). Individual variation could explain the contradictory evidence that exists for load carriage economy, particularly given the small sample sizes (*n* = <10) used in previous studies (Maloiy *et al.* 1986; Charteris *et al.* 1989; Lloyd and Cooke, 2000; Abe *et al.* 2004). However, individual variation in loaded walking economy has not been reported elsewhere. In order to assess the individual variation associated with load carriage economy, the day-to-day variation should be considered. In healthy populations, a mean CV of ~ 5-9% variation has been reported for unloaded walking economy (de Mendonca and Pereira, 2008; Wergel-Kolmert and Wohlfart, 1998; Blessinger et al. 2009; Darter, Rodriguez and Wilken, 2013). This is less reliable than the mean CV of ~ 1.5 – 5% that has been reported for running economy (Periera, Freedson and Maliszweski, 1994). Indeed, the between day reliability of exercise economy appears to increase as the intensity of exercise increases for both walking (de Mendonca and Pereira, 2008) and running (Periera, Freedso n and Maliszweski, 1994; Periera and Freedson, 1997). As such, it would be reasonable to assume that the day-to-day variation in loaded walking economy could be lower than that of unloaded walking, due to the increase in exercise intensity. Our research group have found good day-to-day reliability for load carriage economy with light (7kg) and heavy (20kg) loads across a range of walking speeds (3 $km{\cdot}h^{-1}$ – 6 $km{\cdot}h^{-1}$), with mean CV ranging from 1.75 – 4.17% (Hudson *et al*. 2017).

This paper provides a further analysis of data from previously published research by our group (Hudson *et al.*, 2018). The aim of that research was to assess influence of sagittal plane trunk movements with different load carriage methods on economy. In summary, we found differences in load sagittal plane trunk movements between methods, but no difference in economy. Despite not finding any difference in load carriage economy between methods when assessing the group means, there did appear to be a large amount of individual variation. As such, the aim of this paper is to investigate the extent of the individual variation in economy in the three methods (back-, back and front combined-, and head-loading) with which energy saving phenomenon have been previously reported. It was hypothesised that, in a larger sample of participants than reported in much of the published load carriage literature, there would be a considerable amount of individual variation in load carriage economy.

2. METHODS

2.1. Participants:

Eighteen females participated in this research (age 23 ± 3.8 years, mass 61.1 ± 10.7 kg, stature 1.59 ± 0.81 m). Participant physical characteristics are shown in table 1. All participants had at least 5 years of head-loading experience, were apparently healthy and provided written informed consent to participate. This research complied with the tenets of the Declaration of Helsinki. The research was approved by the institutional ethics committee at the University of Abertay Dundee and the Cape Peninsula University of Technology.

Table 1. Mean, standard deviation, coefficients of variation, maximum and minimum values for participant physical characteristics.

	Age (years)	Stature (m)	Body mass (kg)	BMI (kg/m^2)
Mean	23	1.59	61.1	24.2
Standard deviation	4	0.81	10.8	4.1
Coefficients of variation (%)	17	5.12	17.6	16.8
Maximum	29	1.77	85.4	31.7
Minimum	18	1.39	48.2	19.2

2.2. Experimental Design:

Participants completed one habituation session and three separate main trials at the Human Performance Laboratory at the Cape Peninsula University of Technology. Main trials differed by method of load carriage. The three methods of load carriage were head, back or evenly split between the front and back of the torso (combined back and front-loading). Each trial was separated by a minimum of 72 hours. The order of main trial conditions was randomised using a Latin squared design and picking marked pieces of paper out of a hat. For each trial, participants walked at $3km{\cdot}h^{-1}$ on a motorised treadmill (Genesis, South Africa) with loads of 0, 3, 6, 9, 12, 15 and 20kg. To achieve a steady rate of oxygen consumption, each walking period lasted four minutes and were separated by two minutes of rest (Poole and Richardson, 1997). Participants were asked to maintain a similar diet and refrain from moderate-vigorous exercise and alcohol consumption in the 24 hours prior to each test.

2.3. Experimental Procedures:

2.3.1. Load Carriage Methods:

A commercially available backpack (45 litre Karrimor Alpiniste, Karrimor, UK) was used for the back-loading method. A plastic bucket with a capacity of 20 litres was used for the head-loading method. A commercially available doublepack (Featherlite Freedom, AARN, New Zealand) was used for the combined back and front-loading device. The doublepack consisted of a backpack with two balance pockets that attached to the shoulder straps at the front of the torso. In the head-loading condition, a piece of cloth was used as a cushion between the bucket and the head. Each load mass consisted of sandbags of known mass, allowing the actual load to be within 50g of the nominal load, and the load carriage device itself.

2.3.2. Habituation:

The habituation session was used to familiarize the participants with the experimental protocol and equipment. A typical habituation session lasted for approximately 20 minutes. All volunteers completed a health screen questionnaire and a load carriage history questionnaire prior to taking part in any exercise. At the start of each session, participants body mass (Seca Scales, Seca, UK) and stature (Seca stadiometer, Seca UK) were recorded. Participants then walked on the treadmill at 3km·h^{-1}, while wearing the facemask for gas analysis (K4b2, COSMED, Italy), and carrying the heaviest load mass in each load carriage device.

2.3.3. Main Trials:

Body mass was measured at the beginning of each trial. The face mask for gas analysis and a heart rate monitor (Polar, Finland) were then fitted. Participants were then asked to walk on the treadmill at 3km·h^{-1} (0% gradient) for four minutes while carrying no additional load. This was followed by two-minutes of rest, during which the appropriate load carriage method was fitted for the trial condition. Following the rest, participants walked on the treadmill at the same speed for four minutes while carrying the initial load of 3kg. This walking and rest pattern continued, with a gradual increase in the load carried (3, 6, 9, 12, 15 and 20kg) in subsequent periods of walking.

Expired air was continuously measured throughout each walking period using a breath-by-breath analysis system (K4b2, COSMED, Italy). The Extra Load Index (ELI), shown in equation 1, was used to assess load carriage economy (Lloyd *et al*. 2010a). The average $\dot{V}O_2$ in the final 60-seconds of each stage was used in the calculation of ELI.

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

where mlO_{2U} and mlO_{2L} refer to unloaded and loaded $\dot{V}O_2$, respectively. A value of 1 indicated a proportional increase in $\dot{V}O_2$ as the additional load mass supported by the muscles increased. Values of less than 1 indicated a relatively lower metabolic energy cost, while a value greater than 1 indicated a relatively higher metabolic cost. The gross metabolic rate per kilogram of body mass (W/kg) was also calculated from $\dot{V}O_2$ and $\dot{V}CO_2$ using the Brockway (1987) equation and assuming zero protein metabolism.

2.4. *Data Analysis:*

Means and standard deviations for $\dot{V}O_2$, ELI and the gross metabolic rate were calculated for each load method and load mass combination. Coefficients of variation (CV) were calculated to assess variation in each condition. IBM SPSS 22 was used for statistical analysis. A two-way ANOVA with repeated measures (load carriage method x load mass) was conducted on the $\dot{V}O_2$, ELI and gross metabolic rate data to assess for significant effects and interactions. Post-hoc tests with a Bonferroni correction were used to assess significant main effects. Statistical significance was set at $p \leq 0.05$. Simple Pearson's correlation was used to assess the relationship between ELI values and the participant's physical characteristics (body mass, stature and BMI). Linear multi-level models (MLM), using maximum likelihood estimation, were created for the $\dot{V}O_2$, ELI and gross metabolic rate data, with each method of load carriage. The MLM's were used to estimate the variance between participants (σ^2_u) and between load mass (σ^2_e). Intra-class Correlation Coefficients (ICC) were calculated from the variance components in each MLM to represent the proportion of total variability in the outcome that was attributable to individual differences.

3. RESULTS

3.1. $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)

Table 1 shows the mean, standard deviation and coefficients of variation for $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) across all loading conditions. There was no significant difference between loading methods for $\dot{V}O_2$ when walking unloaded ($p = 0.761$). The mean CV for $\dot{V}O_2$ between the three unloaded walking trials was 13%. $\dot{V}O_2$ increased significantly with an increase in load mass ($p = 0.001$) with post-hoc analysis indicating that that $\dot{V}O_2$ increased significantly from the unloaded walking condition with 9, 12, 15 and 20kg ($p \leq 0.05$). However, the difference in the $\dot{V}O_2$ between the load carriage methods was not significant ($p = 0.814$). There appeared to be a similar pattern of response between each of the load carriage methods (table 2), which was confirmed by a lack of interaction between load carriage method and load mass ($p = 0.151$).

The magnitude of standard deviations and coefficients of variation indicates the variability in $\dot{V}O_2$ across the different methods (table 2). There was a significant estimated variance between participants $\dot{V}O_2$ with the head-loading method ($\sigma^2_u = 2.34$, standard error = 0.81, $p < 0.01$), the back-loading method ($\sigma^2_u = 2.26$, standard error = 0.79, $p < 0.01$) and the back/front loading method ($\sigma^2_u = 2.00$, standard error = 0.67, $p < 0.01$). The estimated variance in $\dot{V}O_2$ between load mass conditions was also significant for head-loading ($\sigma^2_e = 0.64$, standard error = 0.08, $p < 0.01$), back-loading ($\sigma^2_e = 0.80$, standard error = 0.10, $p < 0.01$) and back/front-loading ($\sigma^2_e = 0.43$, standard error = 0.06, $p < 0.01$). The ICC values for individual differences in $\dot{V}O_2$ as a proportion of the total variance were 0.78, 0.74 and 0.82 for head-, back- and back/front-loading, respectively.

Table 2. Mean, standard deviation (SD) and coefficient of variation (CV) for $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) values with each loading method and load mass.

	0kg	3kg	6kg	9kg	12kg	15kg	20kg
Head							
$\dot{V}O_2$	10.20	10.97	10.71	11.09	11.25	11.73	12.73
SD	1.50	1.59	1.65	1.73	1.85	1.80	2.09
CV (%)	14.71	14.49	15.41	15.60	16.44	15.35	16.42
Back							
$\dot{V}O_2$	10.35	10.34	10.63	10.70	11.39	12.10	12.99
SD	1.42	1.59	1.63	1.49	1.74	2.09	2.25
CV (%)	13.72	15.38	15.33	13.93	15.28	17.27	17.32
Back/Front							
$\dot{V}O_2$	10.42	10.88	11.01	11.19	11.63	11.91	12.79
SD	1.18	1.47	1.45	1.57	1.74	1.69	1.95
CV (%)	11.32	13.51	13.17	14.03	14.96	14.19	15.25

3.2. Load carriage economy

Table 3 shows the mean, standard deviation and coefficients of variation for ELI values across all loading conditions. ELI values were not significantly different between the different methods of load carriage ($p = 0.483$). With all load mass combined, ELI values were 0.95 ± 0.11 for head-loading, 0.93 ± 0.08 for back-loading and 0.94 ± 0.06 for combined back and front-loading. There was a significant difference in ELI between the mass of the load carried ($p = 0.001$) but there were no significant interaction effects (load method x load mass $p = 0.094$).

With the back-loading method, ELI decreased from 0.95 with 3kg to 0.90 with 9kg. ELI then increased from 9kg with the 15kg and 20kg loads. In the back and front combined loading condition, ELI decreased from 0.99 with 3kg to 0.91 and 0.92 with the 15kg and 20kg loads, respectively. For head-loading the highest ELI was with the 3kg load (1.03) and the lowest was the 12kg load (ELI = 0.92). The large magnitude of standard deviations and coefficients of variation indicates the large variability in ELI values across the different methods (table 3). There was significant variance between participants for ELI values with head-loading (σ^2_u = 0.008, standard error = 0.002, $p < 0.01$), the back-loading (σ^2_u = 0.003, standard error = 0.001, $p = 0.015$) and the back/front loading (σ^2_u = 0.002, standard error = 0.001, $p = 0.013$). The estimated variance in ELI between load mass conditions was also significant for head-loading (σ^2_e = 0.005, standard error = 0.001, $p < 0.01$), back-loading (σ^2_e = 0.004, standard error = 0.001, $p < 0.01$) and back/front-loading (σ^2_e = 0.002, standard error = 0.001, $p < 0.01$). The ICC values for individual differences in ELI as a proportion of the total variance were 0.63, 0.42 and 0.44 for head-, back- and back/front-loading, respectively.

Table 3. Mean, standard deviation (SD) and coefficient of variation (CV) values for Extra Load Index (ELI) with each load method and mass combination.

	3kg	6kg	9kg	12kg	15kg	20kg
Head						
ELI	1.03	0.96	0.95	0.92	0.93	0.94
SD	0.08	0.08	0.11	0.09	0.15	0.14
CV (%)	7.61	8.21	11.49	9.90	16.46	15.21
Back						
ELI	0.95	0.93	0.90	0.92	0.93	0.94
SD	0.06	0.06	0.07	0.10	0.10	0.11
CV (%)	6.39	6.88	7.34	10.76	11.17	11.77
Back/Front						
ELI	0.99	0.96	0.93	0.93	0.91	0.92
SD	0.06	0.06	0.05	0.05	0.07	0.09
CV (%)	6.01	6.32	5.16	5.75	7.55	9.72

3.3. Metabolic rate

Table 4 shows the mean, standard deviation and coefficients of variation for the metabolic rate across all loading conditions. The metabolic rate per kilogram body mass (W/kg) was not significantly different between load carriage methods ($p = 0.893$). The metabolic rate increased significantly with an increase in load mass ($p = 0.001$) with post-hoc analysis indicating that that the metabolic rate increased significantly from the unloaded walking condition with 6, 9, 12, 15 and 20kg ($p \leq 0.05$). There appeared to be a similar pattern of response between each of the load carriage methods (table 4), which was confirmed by a lack of interaction between load carriage method and load mass (*p* = 0.224). The variance between participants for metabolic rate was significant with head-loading (σ^2_u = 0.25, standard error = 0.09, p < 0.01), the back-loading (σ^2_u = 0.25, standard error = 0.01, p < 0.01) and the back/front loading (σ^2_u = 0.21, standard error = 0.07, p < 0.01). Between load mass conditions, the estimated variance in metabolic rate was also significant for head-loading (σ^2_e = 0.08, standard error = 0.01, p < 0.01), back-loading (σ^2_e = 0.09, standard error = 0.01, p < 0.01) and back/front-loading (σ^2_e = 0.05, standard error = 0.01, p < 0.01). The ICC values for individual differences in metabolic rate were 0.77, 0.73 and 0.80 for head-, back- and back/front-loading, respectively.

Table 4. Mean, standard deviation (SD) and coefficient of variation (CV) values for metabolic rate (W/kg) with each load method and mass combination.

	0kg	3kg	6kg	9kg	12kg	15kg	20kg
Head							
Metabolic rate (W/kg)	3.44	3.70	3.64	3.76	3.82	3.99	4.34
SD	0.48	0.54	0.52	0.57	0.62	0.60	0.69
CV (%)	14.06	14.55	14.35	15.26	16.22	14.99	15.79
Back							
Metabolic rate (W/kg)	3.51	3.51	3.61	3.65	3.88	4.12	4.44
SD	0.48	0.55	0.56	0.50	0.57	0.69	0.75
CV (%)	13.67	15.54	15.55	13.63	14.60	16.74	16.87
Back/Front							
Metabolic cost (W/kg)	3.50	3.68	3.71	3.77	3.95	4.03	4.33
SD	0.39	0.47	0.48	0.52	0.56	0.55	0.63
CV (%)	11.03	12.90	12.93	13.67	14.25	13.58	14.53

Figure 1 shows a noticeably high degree of inter- and intra- individual variability in ELI between loading methods. When all load masses were combined, seven participants had their lowest average ELI values for head-loading, six had lowest ELI values for back-loading and five had lowest ELI values with the back/front method.

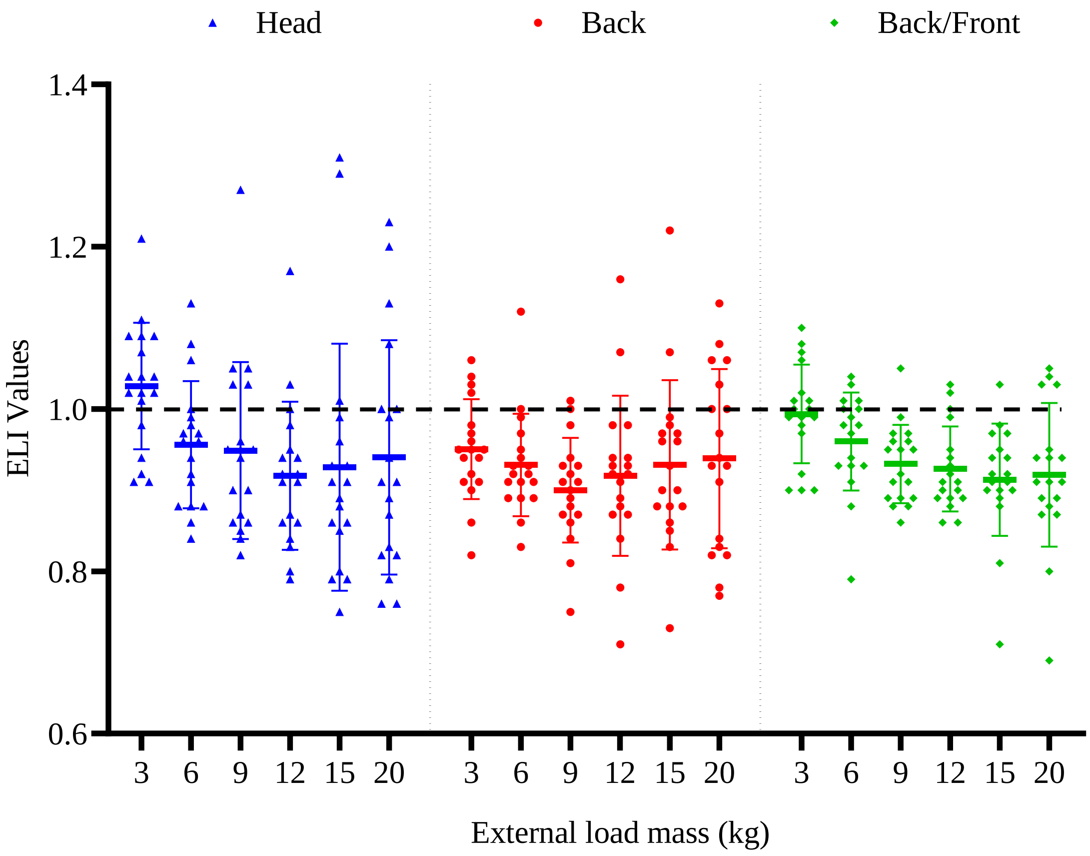

Figure 1. Mean ± SD Extra Load Index (ELI) values for each participant with each loading method across all load masses combined (3, 9, 12, 15 and 20kg). The horizontal dashed line represents the ELI value (ELI = 1) where energy required to support and move the load has risen in proportion to the mass of the load.

There was a difference between methods in the load mass with which the majority of participants had their lowest ELI value (figure 2). In the back-loading method, most participants had their lowest ELI value (most economical) with the 9 kg load (n = 7). In the back/front condition, the majority of participants were most economical with the 20kg load (*n* = 10) and in the head-loading condition, 20kg was the most economical load (*n* = 5). However, in the head-loading condition, there was little difference in the number of participants that were most economical with the 20kg load and the number most economical with the 6kg (*n* = 4), 12kg (*n* = 4) and 15kg (*n* = 3) loads.

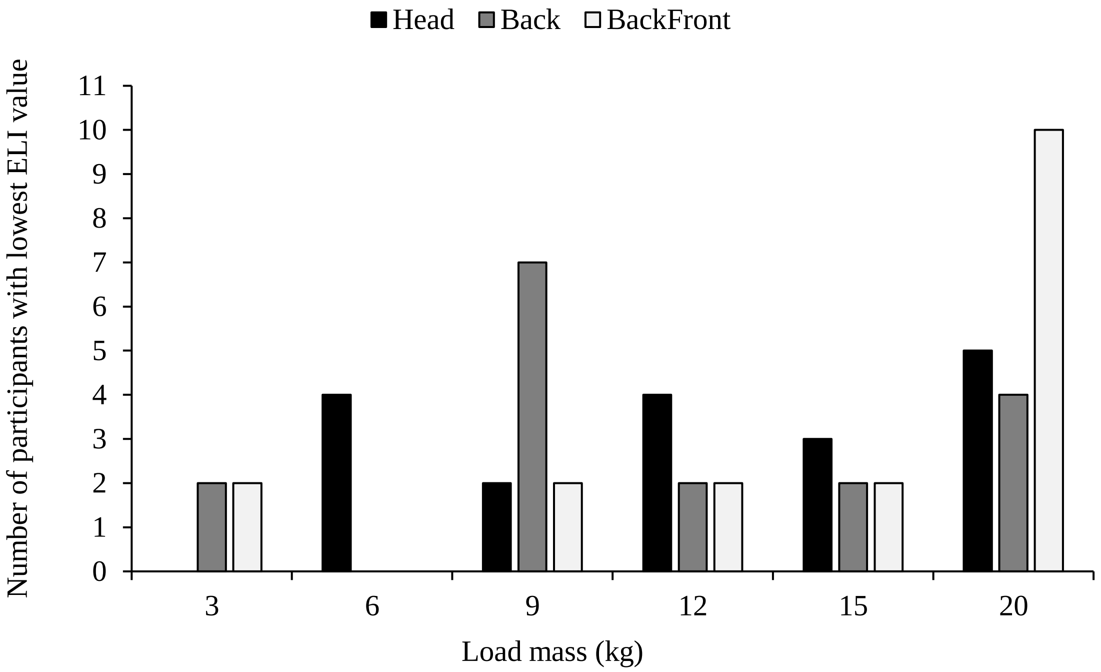

Figure 2. The load mass were participants had their lowest ELI value (most economical) for each method of load carriage

Figure 3 shows how many participants had their highest ELI (least economical) with each of the load mass for each of the loading methods. For each of the loading methods, most participants had their highest ELI values with 3kg. Nine participants had their most economical bout of load carriage when head-loading, five had their most economical bout when back-loading and four were most economical when back/front loading.

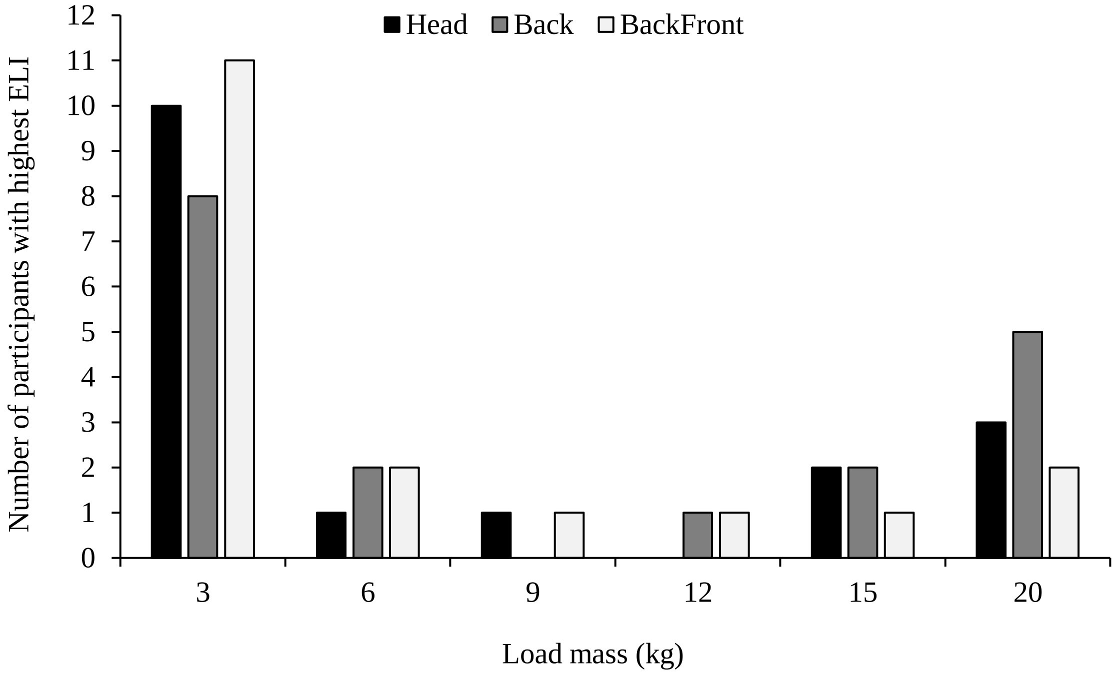

Figure 3. The load mass were participants had their largest ELI (least economical) value for each method of load carriage.

3.4. Relationships between physical characteristics and relative load carriage economy

There were no significant moderate ($r = 0.4 – 0.7$) or strong relationships ($r > 0.7$) between ELI values and stature, body mass or body mass index (BMI) for any of the load method and load mass combinations. The strongest relationship between ELI and physical characteristics was a negative correlation between ELI and BMI for back-loading with 20kg ($r = -0.319$, $p = 0.196$).

4. DISCUSSION

A considerable level of inter-individual variation in relative load carriage economy was found for loads carried on the back, split between the front and back of the torso, and on the head. However, there was no significant difference in group mean values for economy between methods. This finding supports the work of Lloyd *et al.* (2010) who also identified individual variation in back- and head-loading across a range of loads.

Although no significant difference was found for relative load carriage economy between the three methods when assessing mean data, the standard deviations and coefficients of variation in table 2 and table 3 indicate the considerable individual variation in $\dot{V}O_2$ and ELI, respectively. The highest coefficients of variation for ELI was 16%, 12% and 10% for head-, back- and combined back and front-loading, respectively. Our research group has previously shown that the day-to-day reliability (CV) for ELI is 4% and 3% for 7kg and 20kg, respectively, when walking with a rucksack at $3 km \cdot h^{-1}$ (Hudson *et al.* 2017). As such, the individual variation in back-loading economy found in this study cannot be explained by day-to-day variation. This is also likely to be the case for both back/front- and head-loading, particularly given the large coefficients of variation for $\dot{V}O_2$ for both back/front- (highest CV = 15%) and head- (highest CV = 16%) loading compared to the day-to-day variation of ~ 5-9% previously reported for unloaded walking (de Mendonca and Pereira, 2008; Wergel-Kolmert and Wohlfart, 1998; Blessinger et al. 2009; Darter, Rodriguez and Wilken, 2013). Furthermore, the CV in $\dot{V}O_2$ (table 2) and ELI (table 3) increased as the mass of the load increases with all methods, indicating that inter-individual variation in load carriage economy increases as the mass of the load is increased. To account for individual differences in substrate oxidation, the metabolic rate (metabolic power per kg body mass) was also measured. Table 4 shows that the group means for metabolic rate displayed a similar pattern of response to the $\dot{V}O_2$ data (table 2), with the metabolic rate tending to increase as the mass of the load increased in all loading methods. However, there was little difference in the metabolic rate between the three methods. The CV's for metabolic cost were similar to those for the $\dot{V}O_2$ indicating that the variability in metabolic costs was not related to differences in substrate utilisation.

Table 2 shows that mean $\dot{V}O_2$ values increased as load mass increased with all methods. This finding contrasts with the conclusions of Maloiy *et al.* (1986) and Charteris *et al*. (1989) who suggested that African women, with considerable experience of head-loading, can carry up to 20% of their body mass on the head, without their metabolic cost increasing above what they required to walk unloaded at the same speed. The difference between our findings for mean $\dot{V}O_2$ and those of Maloiy *et al.* (1986) and Charteris *et al*. (1989) could be a consequence of sample size ($n = 5$ and $n = 6$ in Maloiy *et al.* (1986) and Charteris *et al.* (1989), respectively). In a much larger sample of experienced head-loaders ($n = 24$), Lloyd *et al*. (2010b) found that, while some participants were able to achieve the same level of economy that had been reported in earlier studies (Maloiy *et al.* 1986; Charteris *et al.*, 1989), the mean data for head-loading economy increased proportionally to the mass of the additional load being carried. In line with the findings of Lloyd *et al. (*2010b), there was no difference in the mean economy data between methods. Despite this, some women were most economical when head-loading, while others were most economical when carrying a load on the back or combined between the front and back.

Figure 1 highlights the inter-individual variation in load carriage economy for each load carriage condition. Despite all women having considerable head-loading experience, some were less economical at head-loading than carrying load on the back or load split between the back and front of the trunk. Female volunteers with a minimum of 5 years of head-loading experience were recruited for this study so that direct comparisons could be made with the work of Maloiy *et al.* (1986) and Charteris *et al*. (1989). Maloiy *et al.* (1986) and Charteris *et al.* (1989) suggested that head-loading economy is dependent on experience. However, with a larger sample of participants, our group has identified that head-loading economy appears to be independent of experience (Lloyd *et al*, 2010) and that minimal habituation appears necessary in order to carry a load on the head in a controlled laboratory environment (Lloyd *et al*. 2011).

Only one participant was most economical with the same load mass across all loading methods, which suggests that economy with one method does not predict economy with another. Figure 2 shows that in the back/front condition, the majority of participant's were most economical with the 20kg load (*n* = 10). This finding offers some support to studies that have found back/front-loading to be more economical than back-loading when carrying heavier loads (Datta and Ramanthan, 1971; Legg and Mahanty, 1985; Lloyd and Cooke, 2000; Lloyd and Cooke, 2011). In the back-loading condition, the majority of participants were most economical when carrying the 9kg load (*n* = 7). This finding supports the work of Abe *et al*. (2004) who reported that a load of 9kg carried on the back yielded a better economy compared to loads of 6kg and 12kg. Abe *et al.* (2004) selected participants based on their physical characteristics with 9kg representing ~15% body mass. The participants in our study varied in body mass (46.6kg - 85.4kg), with a range of 47.9kg – 72.6kg for individuals who were most economical with 9kg carried on the back. Therefore, the good economy associated with the 9kg load does not appear to be a consequence of the load representing a percentage of body mass. This also appears to be the case for the relative economy associated with the 20kg load in the combined back and front-loading condition, with the body mass of participants that found this condition most economical ranging from 48.8kg – 85.4kg.

The lack of moderate or strong relationships between ELI values and body mass, stature or BMI indicates that individual differences in physical characteristics were not related to the individual differences in relative load carriage economy. This data is in line with the findings of Lloyd *et al.* (2010a), who showed that ELI is independent of body composition and the magnitude of the external load carried. The findings of this study also indicate that ELI is not correlated to stature. The lack of correlation between ELI and physical characteristics is also likely to explain the difference in interclass correlation coefficients between the ELI data and both the $\dot{V}O_2$ and metabolic rate data. The intraclass correlation coefficients indicate that variance between individuals represented the largest proportion of the total variance in the $\dot{V}O_2$ (ICC = 0.78, 0.74 and 0.82 for head-, back- and back/front-loading, respectively) and metabolic rate data (ICC =0.77, 0.73 and 0.80 for head-, back- and back/front-loading, respectively). The high proportion of variance assigned to individual differences in $\dot{V}O_2$ and metabolic rate is likely, in part, to be a result of individual differences in body mass (CV = 17.6%). Relative to body mass, the 20kg load condition represented 23.4% of heaviest participant and 41.5% of the lightest participant, with an average of 33.6% ± 5.6%. It is well established that the energy cost of load carriage increases linearly as the mass of the load increases with both absolute and relative loads (Quesda et al., 2000; Bastien et al., 2005; Christie and Scott, 2005). Therefore, differences in the relative loads between participants is likely to account for some of the large variance in $\dot{V}O_2$ found in this study.

There was an overall trend for the standard deviation and coefficients of variation for relative load carriage economy to increase as the mass of the external load increased, with all loading methods. This finding suggests that the magnitude of individual variation in load carriage economy is dependent on the mass of the load. It is possible that the magnitude of walking gait perturbations, as a consequence of increased load mass, varies between individuals, which could then lead to an increased variance in relative load carriage economy with heavier loads. Future research would benefit from assessing the causes of increased individual variation with heavier loads.

The walking speed in this study was selected to allow for direct comparisons with the work of Maloiy *et al.* (1986), Lloyd and Cooke (2000) and Abe *et al*. (2004). A potential limitation of using a set speed, rather than a self-selected speed, is that it might have affected the participants natural walking gait pattern (Martin and Morgan, 1992) and this could have contributed the high levels of individual variation found in this study.

5. Conclusion

Although no difference in mean values for load carriage economy between back-, combined back and front, and head-loading, there was a considerable level of inter- individual variation. As such, future research investigating the metabolic cost of load carriage should consider sample size when making inferences on group mean results. In addition, future research would benefit from investigating the determinants of individual load carriage economy, in order to improve the design of load carriage systems and optimise load carriage economy.

Highlights

- This research shows the existence of a large level of inter-individual variation in load carriage economy, among different methods that position the load close to the centre of mass of the body.
- There was no significant difference in the group mean data for economy with back-, head- and combined front and back-loading.
- Given the large degree of individual variation found in this study, the small sample sizes employed in much of the load carriage literature could explain some of the equivocal findings for the metabolic costs associated with load carriage.
- This research highlights the need for future load carriage research to account for individual variation, particularly when making inferences on the metabolic cost associated with different types of load carriage using group mean data.
- More research is needed to explore the cause of individual differences in load carriage economy in order to optimise load carriage design and performance.

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References

Abe, D., Yanagawa, K., & Niihata, S. (2004). Effects of load carriage, load position, and walking speed on energy cost of walking. *Applied ergonomics*, *35*(4), 329-335.

Bastien, G. J., Willems, P. A., Schepens, B., & Heglund, N. C. (2005). Effect of load and speed on the energetic cost of human walking. *European journal of applied physiology*, *94*(1-2), 76-83.

Blessinger, J., Sawyer, B., Davis, C., Irving, B. A., Weltman, A., & Gaesser, G. (2009). Reliability of the VmaxST portable metabolic measurement system. *International journal of sports medicine*, *30*(1), 22.

Brockway, J. M. (1987). Derivation of formulae used to calculate energy expenditure in man. *Human nutrition. Clinical nutrition*, *41*(6), 463-471.

Charteris, J., Scott, P. A., & Nottrodt, J. W. (1989). Metabolic and kinematic responses of African women headload carriers under controlled conditions of load and speed. *Ergonomics*, *32*(12), 1539-1550.

Christie, C. J., & Scott, P. A. (2005). Metabolic responses of South African soldiers during simulated marching with 16 combinations of speed and backpack load. *Military medicine*, *170*(7), 619-622.

Darter, B. J., Rodriguez, K. M., & Wilken, J. M. (2013). Test–retest reliability and minimum detectable change using the k4b2: oxygen consumption, gait efficiency, and heart rate for healthy adults during submaximal walking. *Research quarterly for exercise and sport*, *84*(2), 223-231.

Datta, S. R., & Ramanathan, N. L. (1971). Ergonomic comparison of seven modes of carrying loads on the horizontal plane. *Ergonomics*, *14*(2), 269-278.

Jones, C. D. R., Jarjou, M. S., Whitehead, R. G., & Jequier, E. (1987). Fatness and the energy cost of carrying loads in African women. *The Lancet*, *330*(8571), 1331-1332.

Heglund, N. C., & Taylor, C. R. (1988). Speed, stride frequency and energy cost per stride: how do they change with body size and gait?. *Journal of Experimental Biology*, *138*(1), 301-318.

Hudson, S., Cooke, C., & Lloyd, R. (2017). The reliability of the Extra Load Index as a measure of relative load carriage economy. *Ergonomics*, *60*(9), 1250-1254.

Hudson, S., Cooke, C., Davies, S., West, S., Gamieldien, R., Low, C., & Lloyd, R. (2018). A comparison of economy and sagittal plane trunk movements among back-, back/front- and head-loading. *Ergonomics*, *61*(9), 1216-1222.

Huang, T. P., & Kuo, A. D. (2013). Mechanics and energetics of load carriage during human walking. *Journal of Experimental Biology*, jeb-091587.

Legg, S. J., & Mahanty, A. (1985). Comparison of five modes of carrying a load close to the trunk. *Ergonomics*, *28*(12), 1653-1660.

Lloyd, R., & Cooke, C. B. (2000). The oxygen consumption with unloaded walking and load carriage using two different backpack designs. *European Journal of Applied Physiology*, *81*(6), 486-492.

Lloyd, R., Hind, K., Parr, B., Davies, S. & Cooke, C. (2010a). The Extra Load Index as a method for comparing the relative economy of load carriage systems, *Ergonomics, 53*(12), 1500-1504.

Lloyd, R., Parr, B., Davies, S., & Cooke, C. (2010b). No'free ride'for African women: a comparison of head-loading versus back-loading among Xhosa women. *South African Journal of Science*, *106*(3-4), 01-05.

Lloyd, R., Parr, B., Davies, S., & Cooke, C. (2011). A kinetic comparison of back-loading and head-loading in Xhosa women. *Ergonomics*, *54*(4), 380-391.

Lloyd, R., & Cooke, C. (2011). Biomechanical differences associated with two different load carriage systems and their relationship to economy. *Human Movement, 12*(1), 65-74.

Maloiy, G. M. O., Heglund, N. C., Prager, L. M., Cavagna, G. A., & Taylor, C. R. (1986). Energetic cost of carrying loads: have African women discovered an economic way?. *Nature, 319*(6055), 668.

Martin, P. E., & Morgan, D. W. (1992). Biomechanical considerations for economical walking and running. *Medicine and Science in Sports and Exercise, 24*(4), 467-474.

Pereira, M. A., Freedson, P. S., & Maliszewski, A. F. (1994). Intraindividual variation during inclined steady-rate treadmill running. *Research quarterly for exercise and sport*, *65*(2), 184-188.

Pereira, M. A., & Freedson, P. S. (1997). Intraindividual variation of running economy in highly trained and moderately trained males. *International journal of sports medicine*, *18*(02), 118-124.

Taylor, C. R., Heglund, N. C., McMahon, T. A., & Looney, T. R. (1980). Energetic cost of generating muscular force during running: a comparison of large and small animals. *Journal of Experimental Biology*, *86*(1), 9-18.

Vilhena de Mendonça, G., & Pereira, F. D. (2008). Between-day variability of net and gross oxygen uptake during graded treadmill walking: effects of different walking intensities on the reliability of locomotion economy. *Applied Physiology, Nutrition, and Metabolism*, *33*(6), 1199-1206.

Wergel-Kolmert, U., & Wohlfart, B. (1999). Day-to-day variation in oxygen consumption and energy expenditure during submaximal treadmill walking in female adolescents. *Clinical Physiology*, *19*(2), 161-168.

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