No 'free ride' for African women: A comparison of head-loading versus back-loading among Xhosa women

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ABSTRACT

Although contrasting evidence exists in the literature as to the economy of head-loading, there is a notion that head-loading is an extremely economical method of load carriage. This has become known as the 'free ride' hypothesis and, although untested, it is widely accepted. The purpose of this study was to test the 'free ride' hypothesis for head-load carriage among African women by comparing the relative economy of head-loading and back-loading. Twenty-four Xhosa women walked on a level treadmill, attempting to carry loads of between 10% and 70% of their body mass (BM) using both a backpack and a head basket. All 24 women carried at least 25% of their BM in both conditions. The relative economy of load carriage was calculated for loads of 10% to 25% of BM. Results indicated that the 'free ride' was not a generalisable phenomenon, with both methods realising economy scores close to unity (1.04 ± 0.19 and 0.97 ± 0.15 for head-loading and back-loading, respectively). The results did, however, reveal significant individual differences in economy scores and it is suggested that analysis of such individual differences in future may well be instructive in understanding mechanisms associated with greater economy in load carriage.

INTRODUCTION

Carrying relatively heavy loads for long distances is still a regular activity for many people in the developing world. The majority of evidence available suggests that the most efficient modes of load carriage result in an additional energy cost similar to the energy cost of carrying additional live mass, and that efficiency is dependent on the position of the load.[1] It has been suggested, however, that carrying loads on the head is particularly efficient and that African women can carry loads of up to 20% of their body mass (BM) without incurring any extra energy cost, the so-called free ride hypothesis.[2,3] This hypothesis is, however, based on very limited data and contains no direct comparison with other load-carriage methods. In this study, we show that, in general, not only is there no 'free ride' for Xhosa women, but also that head-load carriage may be less efficient than carrying loads in a backpack. It is therefore suggested that viable alternatives to head-loading be sought. The results of the study do, however, show that some of the women were able to carry loads very economically in at least one of the conditions, and it will be important for future work to both concentrate on the mechanisms for this efficiency and evaluate the causes of individual variability.

Most of the existing literature relating to load carriage indicates that the energy cost of carrying external loads is similar to[4] or slightly greater than[5] the energy cost of carrying live mass and that the relative economy of load carriage depends, at least in part, on the position of the load.[6] This is demonstrated by the data in Table 1, which are based on the extra load index (ELI).[7] While there are many ways of assessing physical workload, the ELI provides a simple method for comparing load-carriage economy. It is defined as the ratio between loaded oxygen consumption, relative to total load, and unloaded oxygen consumption, relative to BM, that is, where mLO_{2U} and mLO_{2L} refer to unloaded and loaded oxygen consumption, respectively.[7]

$$ELI = \frac{mLO_{2L} \cdot kg\ total\ mass^{-1} \cdot min^{-1}}{mLO_{2U} \cdot kg\ body\ mass^{-1} \cdot min^{-1}} \quad [Eqn\ 1]$$

An ELI value of 1 indicates that the energy cost associated with the external load is the same as that associated with BM, while an ELI > 1 implies reduced economy and an ELI < 1 implies greater economy. This provides an effective method for comparing the relative economy of different load-carriage methods. Table 1 shows ELI values that have been calculated for studies where a measure of energy expenditure during unloaded walking was available. Based on the application of this measure to published data, it seems that methods in which the load is carried close to the trunk are the most economical (Table 1).

There has, however, been other data that suggest that carrying loads on the head may be an extremely economical way of carrying loads.[18] For a variety of reasons (historical, economic and practical), relatively heavy loads are carried on the head in many countries in the developing world. In particular, women across Africa regularly employ some form of head-load carriage, most often to transport essential items such as water and firewood. This practice is currently being challenged at governmental level in South Africa, because of the possibility of harm to the individual. It has been suggested, however, that African women can carry loads of up to 20% of their BM on their heads with no additional energy cost[2] and that any load above 20% of BM incurs a proportional energy cost, for example, carrying 30% of BM requires a 10% increase in energy – the 'free ride' hypothesis.[3] Such a 'free ride' would imply an ELI of 0.83 – a value somewhat lower than that reported either for other methods of load carriage or indeed for head-load carriage in other groups (Table 1). These findings were, however, based on very small participant numbers of five[2] and six.[3] One particularly interesting finding was that this impressive efficiency was independent of the head-load-carrying method used, with three of the five participants carrying loads on the back, supported by a strap around the forehead and two carrying the load directly on the head.[2] This is unexpected, as the kinematics and kinetics of the two methods are very different,[19] with the former likely to provoke a much greater increase in forward lean – a factor known to be associated with reduced economy.[20] In addition to the improved economy, it has also been suggested that head-loading allows relatively heavy loads to be carried with ease, with loads of 70% of BM carried by women

TABLE 1
Calculated extra load index (ELI) values for published data relating to different forms of load carriage

Load position	ELI	Comments
Feet	1.45–1.73 [8]	Increasing ELI with speed, from 4 km·h^{-1} – 5.6 km·h^{-1}
Hands	1.07–1.32 [9]	Increasing ELI with load, from 10 kg – 20 kg
	1.02–1.08 [10]	Light loads – 1.82 kg and 3.64 kg, increasing ELI with speed and load
Backpack	1.04–1.05 [11]	15% and 30% of BM at 6.0 km·h^{-1}
	0.93–1.05 [12]	20% and 40% of BM, at 4.8 km·h^{-1} and 6.1 km·h^{-1}, increasing ELI with speed and load
	0.97–1.01 [13]	20% – 50% of BM, decreasing ELI with load
	1.01 [4]	10.78-kg load at 10.5 km·h^{-1}, demonstrated ELIs within 0.02 of unity across a range of species for loads between 30% and 40% of BM
	1.19 [14]	35% of BM at 3 km·h^{-1}
Back and front pack	1.06 [7]	35% of BM at 3 km·h^{-1}
	0.96 [14]	35% of BM with 24.9 kg at 4.5 km·h^{-1}
Trunk	0.99 [14]	35% of BM with 24.9 kg at 4.5 km·h^{-1}
	0.97 [15]	10% of BM at 4.5 km·h^{-1} with a gradient of 1.5%
	0.97–1.00 [16]	10% of BM at 8 km·h^{-1} – 11 km·h^{-1}, decreasing ELI with increasing speed
Head	0.87–1.06 [17]	Head-strap method, 60 kg – 100 kg at 3.2 km·h^{-1}
	0.96–1.22 [17]	Head-strap method, 60 kg – 100 kg at 3.7 km·h^{-1}
	0.99–1.04 [8]	14 kg, speeds of 4 km·h^{-1} – 5.6 km·h^{-1}

with no discomfort.[2] More recently, when considering load carriage by Nepalese porters, who use the head-strap method, contrasting conclusions with regard to economy have been made.[21,22] The study, which investigated economy in 26 porters, reported a linear increase in energy expenditure with load and concluded that greater economy was not a factor in explaining the extraordinary load-carrying feats of the porters.[21] In contrast, a 20% greater economy for the porters when compared to experienced mountaineers was reported,[22] albeit based on small numbers of participants (n = 3–10) and it was suggested that this could explain some, if not all, of the advantage porters seem to have in carrying heavy loads.[22]

It is important to note, however, that the 'free ride' remains a hypothesis, based on two early studies,[2,3] which examined relatively small numbers of participants. Since those early studies, there has been much interest in explaining the phenomenon reported and various explanatory biomechanical and physiological mechanisms have been proposed.[19,23,24,25,26,27] There has, however, been no systematic attempt to establish either the robustness or the generalisability of the hypothesis, although the 'free ride' hypothesis has been revisited in two studies.[27,28] It was reported that 'something similar' is apparent when loads of less than 20% of BM are carried on the back at slow walking speeds (< 3.6 km·h^{-1}) or when loads of less than 10% of BM are carried in the hands at speeds of 2.4 km·h^{-1}. It is, however, difficult to make direct comparisons between these and previous studies, as economy data is presented as the cost of walking per unit distance within a given load (C_w). An approximation of the ELI values can be obtained by inspection of the graphical data presented and seems to be of the order of 0.9 at the most economical load. The calculation of C_w excludes resting oxygen consumption, and is therefore very likely an underestimate of the true value, given that the resting oxygen consumption will, proportionately, make a larger contribution to unloaded walking and thus subtraction of this constant value from both numerator and denominator will reduce the overall value of the quotient.

While a holistic assessment of load carriage requires more than merely an assessment of energy expenditure and should consider biomechanical factors associated with injury risk, for instance, the aim of this study was to test the 'free ride' hypothesis in African women by making direct comparisons between the energy cost of head- and back-loading in two groups of women who differed only in their experience of head-load carriage.

METHODS

Participants

Twenty-four Xhosa women, 13 with at least 10 years experience of head-load carriage (EXP) and 11 with no experience of head-load carriage (NON), were recruited to take part in the study. All participants gave informed consent for their participation in the study, which had received ethical approval through standard institutional review procedures at both the University of Abertay Dundee and the Cape Peninsula University of Technology. Participants were not paid for their participation in the study, but did receive compensation to cover travel costs. A summary of participant characteristics is presented in Table 2. Independent t-tests indicated no significant differences between the two groups for any of the parameters reported in the table.

Experimental procedures

The women each attended the Human Performance Laboratory at the Cape Peninsula University of Technology on three separate occasions. On the first occasion, participants were screened for any potential contraindications to exercise, stature and mass were assessed and questionnaires relating to load-carriage history were completed. The women were then habituated to the experimental protocol and the equipment to be used. A typical habituation session lasted between 20 min and 30 min and involved the women walking on the treadmill at various speeds both with and without a face mask. In addition, they also practised walking with the two load-carrying devices, a standard 45-L backpack (Karrimor, South Africa) for back-loading and a plastic crate for head-loading (the crate was placed either directly on the head or on a small piece of rolled cloth to provide some cushioning), with and without loads. At the end of the session, the women were asked to walk on the treadmill at a speed that they felt would be comfortable when carrying a heavy load. The chosen speeds, 3.15 ± 0.45 km·h^{-1} and 3.01 ± 0.30 km·h^{-1} for the EXP and NON groups respectively,

TABLE 2
Participant characteristics for the two groups, experienced head-loaders (EXP) and those without experience (NON)

	Age (years)	Stature (m)	Mass (kg)	Speed (km·h^{-1})
EXP	22.5 ± 2.1	1.59 ± 0.05	66.0 ± 12.9	3.15 ± 0.45
NON	21.2 ± 2.4	1.58 ± 0.05	66.7 ± 14.5	3.01 ± 0.30
p-value	0.154	0.564	0.885	0.401

Values of EXP and NON are (mean ± s.d.).
The p-values indicate the result of a comparison (independent t-test) between the two groups for each variable.

were not significantly different (p = 0.401, independent t-test) and were similar to speeds employed in other similar studies.[2,3] The chosen walking speed of each participant was noted and used for the subsequent experimental trials.

On arrival at the laboratory at the next visit, each participant chose at random, via the picking of a suitably marked piece of paper from a hat, the loading method for the first experimental trial. This involved walking, at the previously determined speed, for 4 min unloaded after which, following a 1-min rest, a load of 10% of BM was added, which was carried for a further 4 min. After a further rest of 1 min, the load was increased to 15% and carried for 4 min. This pattern was repeated with loads of 20%, 25%, 30%, 40%, 50%, 60% and 70% of BM or until pain and discomfort led to voluntary cessation of the session. Workloads of 4-min duration were employed based on pilot work that showed that steady-state oxygen consumption was achieved within this time. This duration is consistent with previous studies in this field.[7] The 1-min rest period was used to adjust the carried load and involved the participant standing still on the treadmill while the load was removed, adjusted and then replaced. The load was calculated based on the BM at the habituation session and was made up of the mass of the actual carrying device plus appropriate weightlifting plates (between 2.5 kg and 10 kg) and 100-g sandbags. This allowed the load to be adjusted to within 50 g of the required load. Each participant returned to the laboratory one week later to repeat the experiment with the other loading device.

Data collection and analysis

All participants were fitted with a facemask in line with manufacturer guidelines to ensure that no leaks were present, and expired air was collected throughout the protocol by means of an on-line gas-analysis system (Quark b2, Cosmed, Rome, Italy). The system was calibrated prior to each test in accordance with manufacturer instructions using gases of known concentration and room air. Oxygen consumption was collected breath by breath and reported over 15-s intervals. It was subsequently averaged over the final minute of each workload and the associated ELI values calculated [Eqn 1]. The ELI values were subsequently analysed using an ANOVA (group × load × condition) with repeated measures (SPSS, version 16.0). Maximum load carried was recorded and compared between the groups and conditions by means of a further ANOVA (group × condition) with repeated measures. Pearson's product moment correlation coefficients were calculated to establish relationships between loading conditions and between mean ELI values and anthropometric variables. Independent t-tests were used to assess differences in physical characteristics and walking speed between the two groups and a dependent t-test was used to compare unloaded oxygen consumption between the two trials.

RESULTS

Unloaded oxygen consumption was not different between the successive measurements in each of the two conditions (8.3 ± 2.1 mL·kg^{-1}·min^{-1} vs 7.7 ± 1.8 mL·kg^{-1}·min^{-1} for head- and back-loading respectively, p = 0.261).

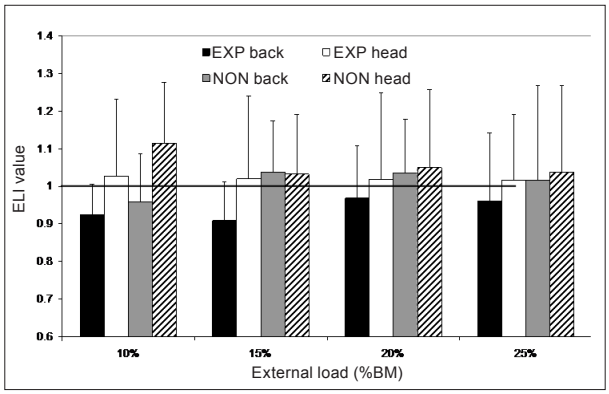
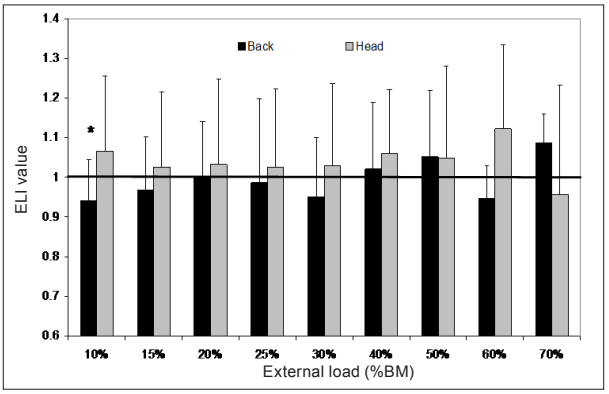


FIGURE 1
Mean + s.d. extra load index (ELI) values for each group in each condition at each load



For loads of 10% – 25% of BM, n = 24; for 30% of BM, n = 20; for 40% of BM, n = 12; for 50% of BM, n = 7; for 60% of BM, n = 3; and for 70% of BM, n = 2.
* Indicates a significant difference (p < 0.05) between head-loading and back-loading.

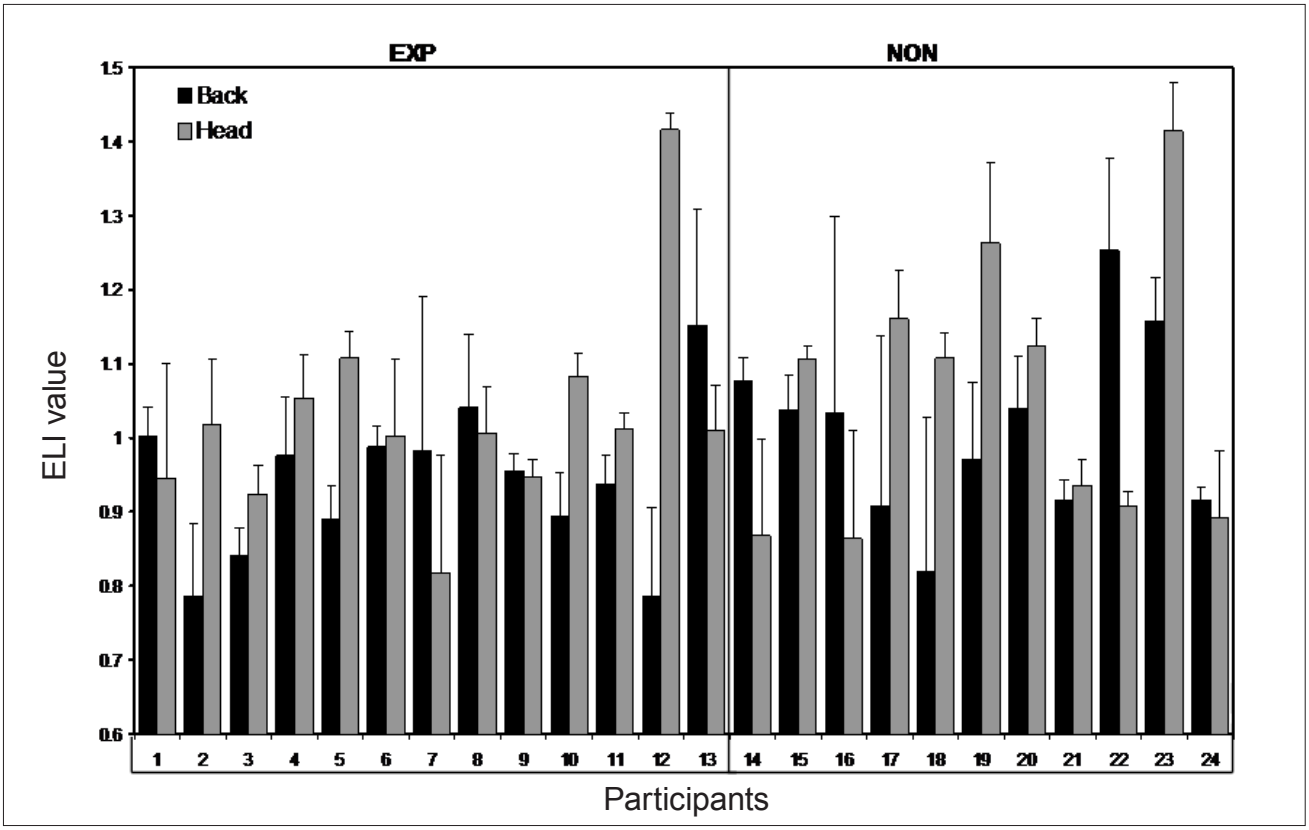
FIGURE 2
Mean + s.d. extra load index (ELI) values for whole group in each condition at each load

Figure 1 shows the ELI values for each group in each of the conditions for loads of up to 25% of BM (the maximum load completed by all 24 participants in both conditions). Statistical analysis revealed no significant difference (p = 0.206) in the relative economy of head-loading and back-loading across all loads (ELI = 1.04 ± 0.19, 0.97 ± 0.15 respectively). Similarly, there was no significant difference between the two groups across all loads (p = 0.186, ELI = 0.98 ± 0.17 for EXP and 1.04 ± 0.18 for NON) or between the different loads (p = 0.891, ELI = 1.00 ± 0.16, 1.00 ± 0.17, 1.01 ± 0.18 and 1.00 ± 0.20 for 10%, 15%, 20% and 25% loads, respectively). There was, however, a significant interaction between carrying method and load (p = 0.053), implying a difference in ELI value associated with each of the loading conditions for at least one of the loads. Post-hoc analysis revealed that this difference was at the 10% load. The mean ELI for back-loading at the 10% load was significantly lower than that for head-loading (95% confidence interval, 0.897–0.986 vs. 0.991–1.15 for back- and head-loading, respectively). There was a significant difference (p = 0.015) between the maximum load carried in each condition, with the average maximum load associated with head-carriage being 42.1 ± 14% of BM versus 51.5 ± 15.8% of BM for back-load carriage. These equate to absolute loads of 27.1 ± 8.3 kg and 33.4 ± 9.6 kg respectively. There was no difference between the loads carried by the two groups (p = 0.382, EXP = 48.8 ± 16.9% of BM, NON = 44.3 ± 13.7% of BM) and no interaction between the two groups and load-carriage method (p = 0.965). Only two women, both from the EXP group, managed to carry 70% of their BM on their head, while seven women (five from the EXP and two from the NON group) managed to carry 70% of their BM on their backs. Figure 2 shows the results for the whole group. The diminishing number of women completing both conditions at the higher loads made interpretation difficult.

One notable result was the high degree of intra- and inter-subject variability in economy both between loading methods and loads (Figure 3). There was no apparent relationship between the conditions for mean ELI value across the 10% – 25% of BM loads (r = 0.147, p = 0.430). Overall, 9 out of 24 participants had lower average ELI values for head-loading than back-loading. This was independent of previous head-loading experience, with 38.5% of the experienced head-loaders exhibiting better economy in head-loading than back-loading and 36.4% of the NON group exhibiting the same tendency. The magnitude of the standard deviations in Figure 3 gives an indication of the variability in ELI value across the different loads.

DISCUSSION

The data presented here for back-loading are broadly consistent with previous studies, with ELI values ranging between 0.94 and 0.99 across all loads.[4,11,12,13,14] The data are also consistent with previous data for head-load carriage,[8,17] with ELI values



Participants 1–13 in EXP group; 14–24 in NON group.

FIGURE 3

Mean + s.d. extra load index (ELI) values for each participant in each condition across loads of 10% – 25% of BM

ranging between 1.03 and 1.07 across all loads. The mean data do not, however, support either the 'free ride' hypothesis, or the view that head-load carriage allows heavy loads to be carried with ease. Indeed, the present study indicates that, on average, the relative economy of head-load carriage in these African women is much less than previously reported; there appears to be no physiological advantage to head-load carrying over back-loading. Even though back-loading shows some tendency to be more economical than head-loading, very few women could carry very heavy loads on their heads, while greater loads could be carried on the back than on the head.

However, closer examination of individual results reveals that it would be possible to select a subset of women who did achieve remarkable levels of economy, in line with the previously reported data. Given the small sample sizes in most of the previous studies on head-loading, this is not altogether unexpected, but lends support to the notion that the 'free ride' hypothesis is not a generalisable finding, when tested with larger, more representative samples of African women. The average ELIs of seven of the women were less than 0.9 for back-loading (all of the women had experience of carrying loads on their backs, as this is the traditional African method of carrying babies and small children), while four women achieved this for head-loading. Remarkably, three of the four most economical head-loaders were women with no experience of head-load carriage. This finding would seem to indicate that structural changes to the spine associated with early and prolonged exposure to head-loading are unlikely to provide explanations for such efficiency in individuals, as previously speculated.[2] It has also been argued that body composition influences load-carriage economy[29] and that the explanation for the remarkable economy observed in some head-load carriers is a consequence of their low body fat,[24] with the extent of the 'free ride' being determined by the combination of fat and external load up to 140% of fat-free mass (FFM). While this argument is helpful in untangling some of the issues relating to the 'free ride' hypothesis, it does not provide support for the hypothesis and would only provide an explanation if all extremely economical load carriers are relatively lean. In the present study, the body mass index (BMI, mean ± s.d.) for the 11 women with average ELIs below 0.9 for either load-carriage method was 26.0 ± 4.1 $kg \cdot m^{-2}$, implying that these women were, if anything, slightly overweight. It might also be expected that if the size of the load relative to FFM is the determinant of economy, there would be a strong relationship between economy across different load-carriage methods. However, in the present study it was apparent that economy in one method of load carrying was not an indicator of economy in the other method. An exploration of relationships between economy and basic anthropometric measurements (mass, stature and BMI) in the present study revealed significant relationships only in relation to head-loading. Both BMI and stature were significantly related to the mean ELI value across 10% – 25% of BM loads. In the case of BMI, this was a moderately positive relationship ($r = 0.482$, $p = 0.017$), which suggests that as BMI increases, the economy of head-load carriage decreases. The relationship between BMI and economy for back-loading was weak and not significant ($r = 0.308$, $p = 0.143$). In the case of stature, there was a significant negative correlation with mean ELI value across loads of 10% – 25% of BM ($r = -0.551$, $p = 0.005$) for head-loading, but not for back-loading ($r = 0.162$, $p = 0.450$). This implies that, for head-loading, taller individuals exhibited better economy. Interestingly, the relationship between stature and ELI value became stronger as loads increased up to 20% of BM with significant *r*-values of -0.485, -0.556 and -0.663 for loads of 10%, 15% and 20% of BM respectively and then diminished at 25% of BM ($r = -0.326$, $p = 0.121$).

The lack of association between economy and load-carriage method, depicted in Figure 3, in addition to the lack of consistency in relationships between anthropometric variables and economy in each of the loading methods, is an important finding. It suggests that cause and effect relationships between economy and efficiency of load carriage are not likely to be explained by a common set of factors for different forms of load carriage in the same individuals, whether or not they are experienced in either or both forms of load carriage under investigation. This suggests that future work, and evaluations of previously completed studies in load carriage, should focus on an evaluation of the mechanisms responsible for the economy of individuals rather

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than expecting one or more mechanism to explain the observed variation within a particular method. This shift in focus, with a view to understanding how particular individuals carry loads more efficiently than others and why particular methods are more efficient for some individuals than others, may provide a better understanding of the interactive effects of factors related to different forms of load carriage. Thus, some of the proposed explanations for the greater economy of head-loading, such as improved energy transfer between gravitational potential energy and kinetic energy[25,26] (based on the five participants of the original study[2]), balancing the loaded segment above the hip[22] (based on five experienced head-loaders carrying loads uphill but with no direct measurement of unloaded walking) and for back-loading at some low-speed–light-load conditions, the interaction of rotative torque and the burden on the lower limbs,[27,28] may be best examined on a case-by-case basis, attempting to account for individual difference rather than seeking general explanations. This may have implications for both military and recreational applications, as it is likely to be the case that either the optimum load-carriage system may be specific to an individual or that particular carrying methods require different techniques. It is clear that individualisation of load-carriage strategies may be impossible for most applications, although in some particularly sensitive cases it may be worthwhile. Nevertheless, an understanding of the factors that lead to improved economy in particular individuals, rather than pooled results, may well provide a useful way forward in the design and customisation of mass-market products.

The present findings, in conjunction with other data that suggest that head-loading is associated with significant and chronic neck pain,[30] suggest that there is a need to not only reconsider the appropriateness of head-loading as a means of transporting heavy loads but also to establish viable alternative methods. Such investigations will need to examine not only the energy expenditure associated with different loading methods, as was the case here, but also biomechanical measures. This will allow for consideration of potential injury and health risks.

CONCLUSION

This study sought to test the 'free ride' hypothesis in African women. The mean data presented provide no support for such a phenomenon, suggesting that, on the whole, both head-loading and back-loading are associated with ELIs close to unity. It was, however, also apparent that there was a significant degree of individual difference in response, with certain individuals achieving something close to a 'free ride' in one or other of the conditions, but not both. It is therefore concluded that, (1) the interactions between load-carriage systems and individuals are complex and future work should be focused on this subject–load–loading system interaction with a view to elucidating the key factors associated with greater economy in load carriage, with the potential to incorporate these findings into systems that can be more readily customised to individual needs and (2) there is a need to explore alternatives to head-loading as a means of load carriage in rural Africa.

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REFERENCES

1. Knapik J, Harman E, Reynolds K. Load carriage using packs: A review of physiological, biomechanical and medical aspects. Appl Ergon. 1996;27:207–216.
2. Maloiy GM, Heglund NC, Prager LM, Cavagna GA, Taylor CR. Energetic costs of carrying loads: Have African women discovered an economic way? Nature. 1986;319:668–669.
3. Charteris J, Nottrodt JW, Scott PA. The 'free ride' hypothesis: A second look at the efficiency of African women headload carriers. S Afr J Sci. 1989;85:68–71.
4. Taylor CR, Heglund NC, McMahon TA, Looney TR. Energetic cost of generating muscular force during running. J Exp Biol. 1980;86:9–18.
5. Bastien GJ, Willems PA, Schepens B, Heglund NC. Effect of load and speed on the energetic cost of walking. Eur J Appl Physiol. 2005;94:76–83.
6. Stuempfle KJ, Drury DG, Wilson AL. Effect of load position on physiological and perceptual responses during load carriage with an internal frame backpack. Ergonomics. 2004;47(7):784–789.
7. Lloyd R, Cooke CB. The relative economy of two different rucksack designs. J Sports Sci. 2000;18:35–36.
8. Soule RG, Goldman RF. Energy costs of loads carried on the head, hands or feet. J Appl Physiol. 1969;27:687–690.
9. Kamon E, Belding HS. The physiological cost of carrying loads in temperate and hot environments. Hum Factors. 1971;13:153–161.
10. Francis K, Hoobler T. Changes in oxygen consumption associated with treadmill walking and running with light hand carried weights. Ergonomics. 1986;29:999–1004.
11. Quesada PM, Mengelkoch LJ, Hale RC, Simon SR. Biomechanical and metabolic effects of varying backpack loading on simulated marching. Ergonomics. 2000;43(3):293–309.
12. Rorke SL. Selected factors influencing the 'optimum' backpack load for hiking. S Afr J Res Sport Physical Educ Rec. 1990;13:31–45.
13. Gordon MJ, Goslin BR, Graham T, Hoare J. Comparison between load carriage and grade walking on a treadmill. Ergonomics. 1983;26:289–298.
14. Legg SJ, Mahanty A. Comparison of five modes of carrying a load close to the trunk. Ergonomics. 1985;28:1653–1660.
15. Myo Thein, Lammert O, Garby L. Effect of trunk load on the energy expenditure of treadmill walking and ergometer cycling. Eur J Appl Physiol. 1985;54:122–124.
16. Thorstensson A. Effects of moderate external loading on the aerobic demand of submaximal running in men and 10 year old boys. Eur J Appl Physiol. 1986;55:569–574.
17. Nag PK, Sen RN. Cardiorespiratory performance of porters carrying loads on a treadmill. Ergonomics. 1978;22:897–907.
18. Bastien GJ, Schepens B, Willems PA, Heglund NC. Energetics of load carrying in Nepalese porters. Science. 2005;308:1755.
19. Charteris J, Scott PA, Nottrodt JW. Metabolic and kinematic responses of African women headload carriers under controlled conditions of load and speed. Ergonomics. 1989;32:1539–1550.
20. Lloyd R, Cooke CB. Relationships between physiological and postural adjustments to load carriage for rucksack designs. J Sports Sci. 2000;18:25–26.
21. Malville NJ, Burns WC, Lim HA, Basnyat R. Commercial porters of eastern Nepal: Health status, physical work capacity and energy expenditure. Am J Hum Biol. 2001;13:44–56.
22. Minetti AE, Formenti F, Ardigo LP. Himalayan porter's specialization: Metabolic power, economy, efficiency and skill. Proc Roy Soc B. 2006;273:2791–2797.
23. Alexander RM. Making headway in Africa. Nature. 1986;319:623–624.
24. Jones CDR, Jarjou MS, Whitbread RG, Jequier E. Fatness and the energy cost of carrying loads in African women. The Lancet. 1987;12:1331–1332.
25. Heglund NC, Willems PA, Penta M, Cavagna GA. Energy saving gait mechanics with head-supported loads. Nature. 1995;375:52–54.
26. Cavagna GA, Willems PA, Legramandi MA, Heglund NC. Pendular energy transduction within the step in human walking. J Exp Biol. 2002;205:3413–3422.
27. Abe D, Yanagawa K, Niihata S. Effects of load carriage, load position, and walking speed on energy cost of walking. Appl Ergon. 2004;35:329–335.
28. Abe D, Muraki S, Yasukouchi A. Ergonomic effects of load carriage on the upper and lower back on metabolic energy cost of walking. Appl Ergon. 2008;39:329–335.
29. Lyons J, Allsopp A, Bilzon J. Influences of body composition upon the relative metabolic and cardiovascular demands of load carriage. Occup Med. 2005;55:380–384.
30. Lloyd R, Parr B, Davies S, Cooke C. Subjective perceptions of load carriage on the head and back in Xhosa women. Appl Ergon. 2010;41:522–529.