The Extra Load Index (ELI) as a method for comparing the relative economy of load carriage systems

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Abstract

The Extra Load Index (ELI) has been proposed as a suitable method of assessing the relative economy of load carriage systems. The purpose of this study was to determine, based on empirical evidence, that the ELI can accommodate variations in both body composition and added load. Thirty women walked carrying loads of up to 70% BM at self selected walking speeds whilst expired air was collected. In addition each of the women had body composition assessed via DXA. Results show that the ELI is independent of body composition variables, the magnitude of additional loads and the speed of progression. Consequently it is suggested that it represents an appropriate method of comparing load carriage systems in both scientific and commercial arena.

Key words

Physiology, anthropometry, product design, ergonomics tools and methods

50 word statement

We demonstrate that the Extra Load Index (ELI) is independent of body composition, added load and speed and is therefore an appropriate method to generalise comparisons of load carriage systems. It has the advantage of being easily understood by manufacturers and consumers whilst retaining appropriate scientific precision.

1.0 Introduction

A number of approaches have previously been taken when investigating the economy of load carriage. All of the methods are based on measurement of expired air and calculation of oxygen consumption. Some studies have reported what might be considered first order data, reporting oxygen consumption either in: absolute terms (e.g. Chung *et al*, 2005); relative to body mass (e.g. Lloyd and Cooke 2000a); relative to total mass (e.g. Balogun *et al*, 1986) or as energy expenditure calculated from oxygen consumption using standard conversion factors (e.g. Marsh *et al*, 2006). Others have reported second order data such as the energy cost of walking, C_w (e.g. Abe *et al*, 2004) or the net metabolic power P_{net} (e.g. Bastien *et al*, 2005). In these latter cases the energy expenditure is reported net of resting energy expenditure, i.e. the energy expenditure required to walk minus the energy expenditure required to stand. Methods that consider net energy consumption have been found useful in studying the energetic cost of unloaded walking as they provide a better measure of the energy cost attributable to the action of walking (Browning *et al*, 2006). We argue that this logic can be extended to load carriage and that the cost of transporting a load is best represented by factoring out the energy cost of unloaded walking. This is an approach based on the seminal work of Taylor *et al* (1980). We have re-expressed their original equations in a simpler form to produce a single, dimensionless index, the Extra Load Index (ELI) (equation 1) that allows for direct comparison of the relative economy of different load carriage systems (LCS). An ELI of 1 indicates that the additional energy cost of carrying a load is the same as carrying 'live mass' whilst values greater than 1 identifies a relatively greater cost and values less than 1 a relatively lower cost.

Equation 1:

$$\mathrm{ELI} = \frac{\mathrm{mlO}_{2_L} \cdot \mathrm{kg\ total\ mass}^{-1} \cdot \mathrm{min}^{-1}}{\mathrm{mlO}_{2_U} \cdot \mathrm{kg\ body\ mass}^{-1} \cdot \mathrm{min}^{-1}}$$

where $ml0_{2U}$ and $ml0_{2L}$ refer to unloaded and loaded oxygen consumption respectively.

From a theoretical perspective, the ELI has a distinct advantage over other methods as it accounts for individual variability in walking gait. Given that most of the available literature indicates that the cost of carrying extra load is similar to, but slightly greater than, the cost of carrying live mass (e.g. Taylor *et al*,

1980) then it is likely that the additional element of energy expenditure, above that required simply to support and move the load, is associated with biomechanical changes that represent acute perturbations from an individual's normal gait pattern (Martin and Morgan, 1992; Cavanagh and Williams, 1982). Furthermore it has been suggested that these normal gait patterns represent the most economical solution for an individual (Martin and Morgan, 1992). Thus a measure of loaded economy that accounts for unloaded movement economy has significant utility and merit since the energetic cost of carrying a load can be conceptualised as: energy cost of unloaded movement at a given speed + energy cost of supporting and moving a given load ± net changes in energetic cost of movement as a consequence of changes in the kinetics and kinematics of movement resulting from the interaction of load, speed and LCS. When the final term is 0 the ELI will be 1 and any deviation from unity represents the relative economy of a particular load/speed/LCS interaction. The value of the ELI will reflect the changes in energetic cost of movement associated with additional load making it sensitive to changes in economy associated with additional loads for any given load-speed combination for any load carriage system. Lloyd and Cooke (under review) have reported significant relations ships between the ELI and various kinematic and kinetic parameters in two different LCS. For example the relationship between the increase in forward lean from heel strike to mid support and ELI was significant for a double pack ($r=-0.867$, $P=0.005$) but not for a backpack ($r=0.454$, $P=0.258$).

From a practical perspective the use of a simple, dimensionless, index of loaded economy would be of value to manufacturers and developers as it is likely to be easier to understand for a non-scientific audience than the more traditional approaches.

The utility of the ELI depends to some degree on its use as a comparative tool. The ELI has previously been used to compare relative economy across a range of studies where measures of unloaded oxygen consumption were available. A summary is presented in Table 1.

Table 1. Calculated ELI values for published data relating to different forms of load carriage. Adapted from Lloyd *et al* (2010).

Load Position	**ELI**	**Comments**
Feet		
Soule and Goldman (1969)	1.45 – 1.73	Increasing ELI with Speed for 4-5.6 km·h^{-1}
Hands		
Kamon and Belding (1971)	1.07 – 1.32	Increasing ELI with Load from 10-20 kg
Francis and Hoobler (1986)	1.02 – 1.08	Light loads – 1.82 and 3.64 kg, increasing ELI with speed and load
Back		
Quesada *et al* (2000)	1.04 – 1.05	15% and 30% BW 6.0 km·h^{-1}
Lloyd and Cooke (2000b)	1.12 – 1.27	35% BM, 3.0 km·h^{-1}, various gradients (-27% to 20%)
Bilzon *et al* (2001)	0.99	18 kg load, 9.5 km·h^{-1}
Rorke (1990)	0.93 – 1.05	20% and 40% BM, 4.8 and 6.1 km·h^{-1}, increasing ELI with Speed and Load
Gordon *et al* (1983)	0.97 – 1.01	20% -50% BM, decreasing ELI with load
Taylor *et al* (1980)	1.01	10.78 kg load, 10.5 km·h^{-1}, demonstrated ELI's within 0.02 if unity across a range of species for loads between 30 and 40% BM
Legg and Mahanty (1985)	1.19	35% BM, 3.0 km·h^{-1}
Lloyd *et al* (2010)	0.93 – 1.09	Self selected walking speed, loads 10-70%BM
Back and Front		
Lloyd and Cooke (2000b)	1.04 – 1.24	35% BM, 3.0 km·h^{-1}, various gradients (-27% to 20%)
Legg and Mahanty (1985)	0.96	35% BM, 24.9 kg, 4.5 km·h^{-1}
Trunk		
Legg and Mahanty (1985)	0.99	35% BM, 24.9 kg, 4.5 km·h^{-1}
Myo Thein *et al* (1985)	0.97	10% BM, 4.5 km·h^{-1}, 1.5% gradient
Thorstensson (1986)	0.97 – 1.00	10% BM, 8-11 km·h^{-1}, decreasing ELI with increasing speed
Head		
Nag and Sen (1978)	0.87 – 1.06 0.96 – 1.22	Head strap method, 60 – 100 kg 3.2 km·h^{-1} Head strap method, 60 – 100 kg 3.7 km·h^{-1}
Soule and Goldman (1969)	0.99 – 1.04	14 kg, speeds of 4 -5.6 km·h^{-1}
Lloyd *et al* (2010)	0.95 – 1.11	Direct head-loading, self selected walking speed, loads 10-70%BM

The data in Table 1 indicates that the ELI is sensitive enough to differentiate between load carriage systems. In order for the ELI to be a universal index of load carriage economy suitable for comparing across load carriage systems it needs to accommodate variations in the external load carried, the walking speed employed and differences in body composition of study participants. Based on its definition this should be the case. The purpose of this study, therefore, was to establish, based on empirical data, if the ELI can appropriately accommodate variations in body composition factors, magnitude of external load and walking speed.

2.0 Methods

2.1 Participants

Thirty women 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 Cape Peninsula University of Technology.

2.2 Load Carriage Performance

All performance data was collected at the Human Performance Laboratory of Cape Peninsula University of Technology. Participants visited the laboratory on two occasions. On the first visit participants were screened for any potential contraindications to exercise before stature and mass were assessed. The women were then habituated to the experimental protocol. A typical habituation session lasted between twenty and thirty minutes and involved the women walking on the treadmill at various speeds both with and without a face mask. In addition they also tried out the load carrying device, a standard 45l backpack (Karrimor, SA) 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 walking speed (mean 3.01 ± 0.44 $km \cdot h^{-1}$) of each participant was noted and used for the subsequent experimental trials.

On arrival at the laboratory at the next visit each participant walked, at the previously determined speed, for four minutes unloaded and then, after a one minute rest, a load of 10% body mass was added which was carried for a further four minutes. After a further rest of one minute the load was increased to 15% and carried for four minutes. This pattern was repeated with loads of 20%, 25%, 30%, 40%, 50%, 60% and 70% of body mass or until pain and discomfort led to voluntary cessation of the session. The load was calculated based on the body mass at the habituation session and was made up of the mass of the backpack plus appropriate weightlifting plates, (between 2.5kg and 10kg), and 100g sandbags, which allowed the load to be adjusted to within 50g of the required load.

All participants were fitted with a face mask and expired air was collected throughout the protocol by means of an on-line gas analysis system (Quark b2, Cosmed, Rome). The system was calibrated prior to each test in accordance with manufacturer's instructions using gases of known concentration and room air.

2.3 Body Composition Assessment

Physical measurements were made with subjects wearing a hospital gown and all metal artefacts removed. Total body, anteroposterior lumbar spine (L2 to L4) and total hip BMD were measured using dual energy X-ray absorptiometry (DXA) (Discovery W, Hologic Inc. US), at the University of Cape Town/MRC Research Unit for Exercise and Sports Medicine, South Africa. Machine calibration checks were carried out on a daily basis. All scanning and analyses were made by a trained operator and intra-observer variation was 0.87% at the hip and 0.98% at the lumbar spine.

2.4 Data Analysis

Oxygen consumption was averaged over the final minute of each workload and the associated ELI values calculated (Equation 1). Percent body fat (%BF), fat mass (FM), bone mineral content (kg) (BMC) and fat-free soft tissue mass (kg) (LBM) were derived using DXA of the total body. Stature was assessed and recorded to the nearest millimetre (Scales 2000, South Africa). Body mass (BM) was measured and recorded in kg to the nearest 0.1 kg (Scales 2000, South Africa). Body mass index (BMI) was calculated as body mass / (height) ^{2} ($kg \cdot m^{-2}$). External load (EL) was defined as the actual load carried in each trial whilst total mass (TM) was defined as BM+EL. Dead mass (DM) was defined as external load + fat mass (Lyons *et al*, 2005). The LBM:DM ratio (Lyons *et al*, 2005) was calculated by dividing LBM by DM.

The number of participants able to carry prescribed loads diminished beyond the 30% load, consequently the analysis is restricted to loads of 10-30% BM. Pearson Product Moment Correlation Coefficients were calculated to assess the strength of relationships of both body composition variables and external load with ELI values for each load and for pooled data for load 10-30%BM (SPSS v17.0, SPSS Inc.).

3. 0 Results

Details of participant characteristics and body composition variables are shown in table 2. ELI values for each load were as follows: 0.96 ± 0.11, 0.98 ± 0.12, 1.02 ± 0.14, 1.01 ± 0.18 and 1.00 ± 0.17 for loads of 10%, 15%, 20%, 25% and 30% BM respectively.

Table 2. Participant characteristics

Age (years)	22.3 ± 2.9
Body Mass (kg)	65.9 ± 13.1
Stature (cm)	159.1 ± 5.1
Lean Mass (kg)	37.2 ± 4.8
BMC (kg)	2.0 ± 0.25
Fat Mass (kg)	25.1 ± 9.1
% Body Fat	38.0 ± 6.7
BMI ($kg \cdot m^{-2}$)	26.0 ± 5.2

Pearson Product Moment Correlation Coefficients for relationships between ELI values and body composition and loading variables are shown in table 3.

Table 3. Relationship (Pearson Product Moment Correlation Coefficient, *r)* between ELI and selected body composition, external load and speed variables

	10% (n=30)	15% (n=30)	20% (n=30)	25% (n=28)	30% (n=27)	Pooled Data (n=145)
BMC	0.176	-0.059	-0.085	-0.228	-0.035	
FM	0.136	0.246	0.245	0.046	0.139	
LBM	0.111	0.137	0.284	0.255	0.267	
BM	0.157	0.224	0.284	0.126	0.195	
%BF	0.084	0.260	0.203	0.059	0.046	
BMI	0.130	0.216	0.212	0.055	0.132	
EL	0.157	0.224	0.284	0.126	0.195	0.155
TM	0.157	0.224	0.284	0.126	0.195	0.169
DM	0.142	0.240	0.252	0.063	0.156	0.152
LBM:DM	-0.055	-0.249	-.192	0.083	-0.033	-0.119
Speed	0.173	0.173	0.173	0.190	0.179	0.173

4.0 Discussion

Although ELI values have not been reported elsewhere, other than Taylor *et al* (1980) and Lloyd and Cooke (2000b), they can be calculated, based on mean data, for those studies that have reported oxygen consumption for unloaded walking (see Table 1). The ELI values reported here are consistent with these calculated values, being in general just greater than unity. For example ELI values of 1.04-1.05 can be derived from the data of Quesada *et al* (2000) relating to loads of 15%-30% BM carried at 6.0 $km^{.}h^{-1}$, whilst those for the data of Gordon *et al* (1983) range between 0.97 and 1.01 for loads of 20-50%BM, with the lower scores being associated with the higher loads, and the data for Rorke (1990) providing a range of 0.93 – 1.05 for loads of 20 and 40% BM and speeds of 4.8 and 6.1 $km^{.}h^{-1}$, lower speed/load combinations being associated with lower ELI values. Lloyd and Cooke (2000b), examining a backpack and a front-back loading system, showed that the ELI varied differentially with gradient. It is worthy of note that very few papers considering load carriage economy report unloaded oxygen consumption or energy expenditure. We would argue that this is a serious omission and that comparisons to unloaded walking should be standard practice in all assessments of loaded walking, whether they be metabolic, kinematic, kinetic, electromyographic or subjective-perceptual.

The correlations in table 2 confirm that the ELI is independent of body composition variables, the magnitude of external load and walking speed. The first of these is important as it has been argued that individual load carriage performance may be influenced by body composition (e.g. Jones *et al*, 1987; Haisman, 1988, Lyons *et al*, 2005), whilst the latter are important as they allow for comparison across different experimental protocols. It should be noted that the range of speeds employed here were limited, range 1.9 – 4.0 $km \cdot h^{-1}$, and further work may be warranted in this area, comparing across a greater range of speeds. It is, however, the case that calculated ELI values from previous studies employing a greater range of speeds exhibit consistency (Table 1). This independence from body composition, external load and speed supports the theoretical strength of the ELI as a dimensionless index for comparing load carriage economy across different load carriage systems.

Conclusion

Based on the evidence provided here, the Extra Load Index (ELI) represents a useful tool for comparing the metabolic costs of load carriage systems. We would suggest that it should become the standard method for assessment of the economy of load carriage systems and that, in line with this approach, kinematic, kinetic, electromyographic and subjective perceptual assessments should also be referenced to unloaded walking.

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References

Abe, D., Yanagawa, K. and Niihata, S. (2004) Effects of load carriage, load position, and walking speed on energy cost of walking. *Appl. Ergon.* **35:** 329-335

Balogun, J., Robertson, R., Goss, F., Edwards, M., Cox, R. and Metz, K. (1986). Metabolic and perceptual responses while carrying external loads on the head and by yoke. *Ergonomics* **29:** 1623-1635

Bastien, G.J., Willems, P.A., Schepens, B. and Heglund, N.C. (2005) Effect of load and speed on the energetic cost of human walking. *Eur. J. Appl. Physiol.* **94:** 76-83

Bilzon, J., Allsopp, A., Tipton, M. (2001) Assessment of physical fitness for occupations encompassing load carriage tasks. *Occ. Med* **51**:357–361.

Browning, R., Baker, E., Herron, J. and Kram, R. (2006). Effects of obesity and sex on the energetic cost and preferred speed of walking. *J. Appl. Physiol.* **100:** 390-398

Cavanagh, P. R. and Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Med. Sci. Sports Exerc*. **14**, 30-35

Chung, M., Lee, Y., Lee, I. and Choi, K. (2005). Physiological workload evaluation of carrying soft drink beverage boxes on the back. *Appl. Ergon.* **36:** 569-574

Francis, K. and Hoobler, T. (1986) Changes in oxygen consumption associated with treadmill walking and running with light hand carried weights. *Ergonomics* **29:** 999-1004

Gordon, M.J., Goslin, B.R., Graham, T. and Hoare, J. (1983) Comparison between load carriage and grade walking on a treadmill. *Ergonomics* **26:** 289-298

Haisman, M. (1988) Determinants of load carrying ability. *Appl. Ergon.* **19:** 111-121

Jones, C.D.R., Jarjou, M.S., Whitbread, R.G. and Jequier, E. (1987) Fatness and the energy cost of carrying loads in African women *The Lancet* **12:** 1331-1332

Kamon, E. and Belding, H.S. (1971) The physiological cost of carrying loads in temperate and hot environments. *Human Factors* **13:** 153-161

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

Lloyd, R. and Cooke C.B. (2000a) The oxygen consumption associated with unloaded walking and load carriage using two different backpack designs. *Eur J App Phys.*.**81**(6):486-492

Lloyd, R. and Cooke, C.B. (2000b) The relative economy of two different rucksack designs. *Journal of Sports Science* **18:** 35-36

Lloyd, R. and Cooke, C.B. (Under Review) Biomechanical differences associated with two different load carriage systems and their relationship to economy. Submitted to *Human Movement*

Lloyd, R., Parr, B., Davies, S. and Cooke, C (2010). No 'Free Ride' for African women: a comparison of head-loading versus back-loading amongst Xhosa women. *S. Afr. J. Sci.* **106 (3/4):** 50-54

Lyons, J., Allsopp, A. and Bilzon, J. (2005) Influences of body composition upon the relative metabolic and cardiovascular demands of load carriage. *Occ. Med.* **55**: 380-384

Marsh, R., Ellerby, D., Henry, H. and Rubenson, J. (2006). The energetic costs of trunk and distal-limb loading during walking and running in guinea fowl *Numida meleagris*. I. Organisational metabolism and biomechanics. *J. Exp. Biol* **209:** 2050-2063

Martin**,** P. E. and Morgan, D. W. (1992)**.** Biomechanical considerations for economical walking and running. *Med. Sci. Sports Exerc*. **24:**467-474,

Myo Thein, Lammert, O. and Garby, L. (1985) Effect of trunk load on the energy expenditure of treadmill walking and ergometer cycling. *Eur J App Phys* **54:** 122-124

Nag, P.K. and Sen, R.N. (1978) Cardiorespiratory performance of porters carrying loads on a treadmill. *Ergonomics* **22:** 897-907

Quesada, P.M., Mengelkoch, L.J., Hale, R.C and Simon, S.R. (2000) Biomechanical and metabolic effects of varying backpack loading on simulated marching. *Ergonomics*. **43**(3):293-309

Rorke, S.L. (1990) Selected factors influencing the "optimum" backpack load for hiking. *S.Afr. J. Res. Sp. Phys. Ed. Rec.* **13:** 31-45

Soule, R.G. and Goldman, R.F. (1969) Energy costs of loads carried on the head, hands or feet. *J . Appl. Physiol* **27:** 687-690

Taylor, C.R., Heglund, N.C., McMahon, T.A. and Looney, T.R. (1980) Energetic cost of generating muscular force during running. *J. Exp. Biol.* **86** 9-18

Thorstensson, A. (1986) Effects of moderate external loading on the aerobic demand of submaximal running in men and 10 year old boys. *Eur J App Phys* **55:** 569-574