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The energy demands of portable gas analysis system carriage during walking and running

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The energy demands of portable gas analysis system carriage during walking and running

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The aim of this study was to evaluate the carriage of a portable gas analyser during prolonged treadmill exercise at a variety of speeds. Ten male participants completed six trials at different speeds (4, 8 and 12 km h^{-1}) for 40 min whilst wearing the analyser (P) or where the analyser was externally supported (L). Throughout each trial, respiratory gases, heart rate (HR), perceptions of effort and energy expenditure (EE) were measured. Significantly higher EE occurred during P12 ($p = 0.01$) than during L12 (855.3 ± 104.3; CI = 780.7–930.0 and 801.5 ± 82.2 kcal; CI = 742.7–860.3 kcal, respectively), but not at the other speeds; despite this, perceptions of effort and HR responses were unaffected. This additional EE is likely caused by alterations to posture which increase oxygen demand. The use of such systems is unlikely to affect low-intensity tasks, but researchers should use caution when interpreting data, particularly when exercise duration exceeds 30 min and laboratory-based analysers should be used where possible.

Practitioner Summary: There is extensive use of portable gas analysers in many settings. This study suggests that there is no additional effect on energy expenditure until running speeds of 8 km h^{-1} are exceeded. Future work should consider the effects of gas analyser carriage in a wider variety of populations, environments and terrain.

Keywords: load carriage; locomotion; prolonged exercise; oxygen cost; energy expenditure

1. Introduction

The development of ambulatory respiratory gas analysis techniques has allowed indirect calorimetry to be performed in a wide variety of contexts. The main advantage of modern equipment is that it is small, lightweight and consists of discrete components that minimally restrict movement or activity, allowing them to be used in occupational, physical activity, exercise and sporting contexts (Meyer, Davidson, and Kindermann 2005; Reilly et al. 2002; Rundell and Szmedra 1998). This provides the researcher with an ideal opportunity to collect data in environments that are highly ecologically valid and were previously very difficult to study (MacFarlane 2001; Vogler, Rice, and Gore 2010). This technique does, however, require participants to carry the analysis system during task performance, which in itself may affect the responses (Sparks, Orme, and McNaughton 2013). The cost of using different respiratory analysis equipment was first investigated by Siler (1993), who considered the possible effects of an externally supported respiratory mouthpiece use on the oxygen cost of running. Since then, the use of portable gas analysis systems has become much more widespread. The additional external load requirements of the carriage of these systems are typically ~1 kg and are usually attached to either the upper back or chest during data collection (Meyer, Davidson, and Kindermann 2005).

Traditionally, load carriage studies have focused on the evaluation of either load placement or alterations in terrain, during exercise protocols involving low speeds and high additional loads (Attwells et al. 2006; Beekley et al. 2007; Lloyd and Cooke 2000). Conversely, relatively few studies have considered the effects of very light loads (<5 kg or 5% body mass) on the physiological or psychological effects of exercise (Abe, Muraki, and Yasukouchi 2008; Bastien et al. 2005; Stuempfle, Drury, and Wilson 2004). It is, therefore, possible that extremely light loads (~1 kg) have been overlooked in load carriage research due to the perception that they may represent physiologically insignificant additional energy costs. Despite the low additional weight, there are some suggestions that it may increase the energy cost of running-based activities during incremental running protocols (Sparks, Orme, and McNaughton 2013). Small additional energy costs are, however, likely to be exacerbated when exercise intensity is high and duration is more prolonged (Quesada et al. 2000). The purpose of portable gas analysis is to determine a variety of physiological responses in field-based settings, but it is currently unclear whether an additional cost is associated with the equipment carriage, specifically when it is worn during prolonged exercise (>30 min). Furthermore, the quantification of any possible response, in relation to the intensity of activity, has not been established. Therefore, the aim of the current investigation was to determine the energy cost and the

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physiological responses to prolonged treadmill exercise at a range on intensities, whilst carrying a portable gas analysis system.

2. Method

Ten physically active males of mean (SD) age 30.8 (5.1) years, body mass 79.6 (6.9) kg and height 1.81 (0.1) m completed six randomly ordered laboratory treadmill (ERGO, Woodway, Waukesha, WI, USA) tests at three different speeds (4, 8 and 12 km h^{-1}) each lasting 40 min; a duration which has previously been shown to cause alterations in substrate metabolism and physiological responses to load carriage (Quesada et al. 2000) and exercise intensity (Rosenberger, Meyer, and Kindermann 2005). Trials were completed in an ambient laboratory environment of 1006.8 (12.5) mbar pressure at 20.7 (1.9)°C and 50.7 (6.7)% relative humidity. Throughout all trials, respiratory gas analysis was carried out using a portable gas analysis system (Metamax 3B, Cortex Biophysik, Leipzig, Germany), which represented an additional weight of 0.97 kg. This system was calibrated in accordance with the manufacturers' recommendations for volume, temperature, pressure, ambient air and with calibration gases consisting of 4.98% CO_2 and 17.05% O_2 (Cranlea and Co, Birmingham, UK), and has been shown to be both valid and reliable (Vogler, Rice, and Gore 2010). During the control trials, the gas analysis system was configured in a laboratory-based mode (L) with the weight of the analyser suspended adjacent to the treadmill. Conversely, the experimental trial (P) required participants to complete the exercise bouts whilst carrying the analyser in the manufacturers' harness mounted on the chest.

Throughout each exercise trial, respiratory gas responses were measured in 5-min intervals to determine carbohydrate (CHO) and fat oxidation rates (Frayn 1983). The rate of energy expenditure (EE) was then calculated as

$$\mathrm{EE} = \mathrm{CHO\ oxidation\ rate\ (g\ min^{-1})} \times 4.2\ \mathrm{(kcal)} + \mathrm{fat\ oxidation\ (g\ min^{-1})} \times 9.4\ \mathrm{(kcal)}.$$

The total EE for the 40-min trials was determined as the sum of each 5 min EE mean. Ventilation, breathing frequency (B_f), tidal volume (V_T) and heart rate (HR) were also measured at these time intervals. HR was measured using a chest mounted strap (T31, Polar Electro, Kempele, Finland) which transmitted data to the treadmill. Subjective ratings of effort were determined using the rating of perceived exertion (RPE) on a 6–20 scale (Borg 1998). In addition, Likert scales (0–10) were used to determine multi-dimensional components of exertion perceptions, using methods similar to those of Hutchinson and Tenenbaum (2006) for the physical perceptions of exertion (muscle aches) and the physical effort employed in the task (effort).

2.1 *Statistical analysis*

All data were analysed for normality using the Shapiro–Wilk test. Parametric data were analysed using a general linear model ANOVA with repeated measures, and Friedman's tests were used to analyse non-parametric data. *Post hoc* differences were determined using either a Bonferroni pairwise comparison or a Wilcoxon signed-rank test for parametric and non-parametric data, respectively. Significance was accepted at $p < 0.05$, and all procedures were performed using PASW v20 for Windows (IBM, Chicago, IL, USA). All data were reported as mean (± SEM).

3. Results

The rate of EE (Figure 1(a)) was unaffected by gas analyser carriage at both 4 and 8 km h^{-1} ($p = 0.065$ and 0.477, respectively). However, EE was significantly elevated in P12 than in L12 ($p = 0.019$). The rate of EE also significantly increased over time in both L12 and P12 between 5 and 40 min ($p = 0.046$ and 0.029, respectively), but this was not reflected in the lower speed conditions ($p = 0.527$ and 0.698 for 4 and 8 km h^{-1}, respectively). CHO oxidation rates (Figure 1(b)) followed a similar pattern of magnitude-based response, relative to treadmill speed, whereby higher speed significantly elevated CHO oxidation rate ($p < 0.001$) but there were no significant effects of load carriage within each speed condition ($p > 0.05$). During the trials of 8 km h^{-1}, CHO oxidation rates declined between 20 and 40 min ($p = 0.021$). Conversely, speed-based magnitude responses for fat oxidation (Figure 1(c)) were again observed at 4 and 8 km h^{-1}, but only in the trials of 8 km h^{-1}, did fat oxidation rates significantly increase during the final 20 min of the exercise bout ($p = 0.034$). Carriage of the gas analyser at 12 km h^{-1} significantly elevated fat oxidation rates compared with that in L12 ($p = 0.027$). Interestingly, this resulted in a significant interaction effect for condition × time ($p < 0.001$) for the fat oxidation rates. The net effect of elevated fat oxidation rates in P12 was significantly greater total EE (Figure 2) with load carriage ($p = 0.011$) at this speed (855.3 ± 104.3 kcal; CI = 780.7–930.0 and 801.5 ± 82.2 kcal; CI = 742.7–860.3 kcal for P12 and L12, respectively). Alterations in the rate of EE and substrate metabolism were manifest as significantly greater total EE for L8 and P8 compared to the 4 km h^{-1} trials ($p < 0.001$), and greater total EE in the 12 km h^{-1} trials than for both of the lower speeds ($p < 0.001$).

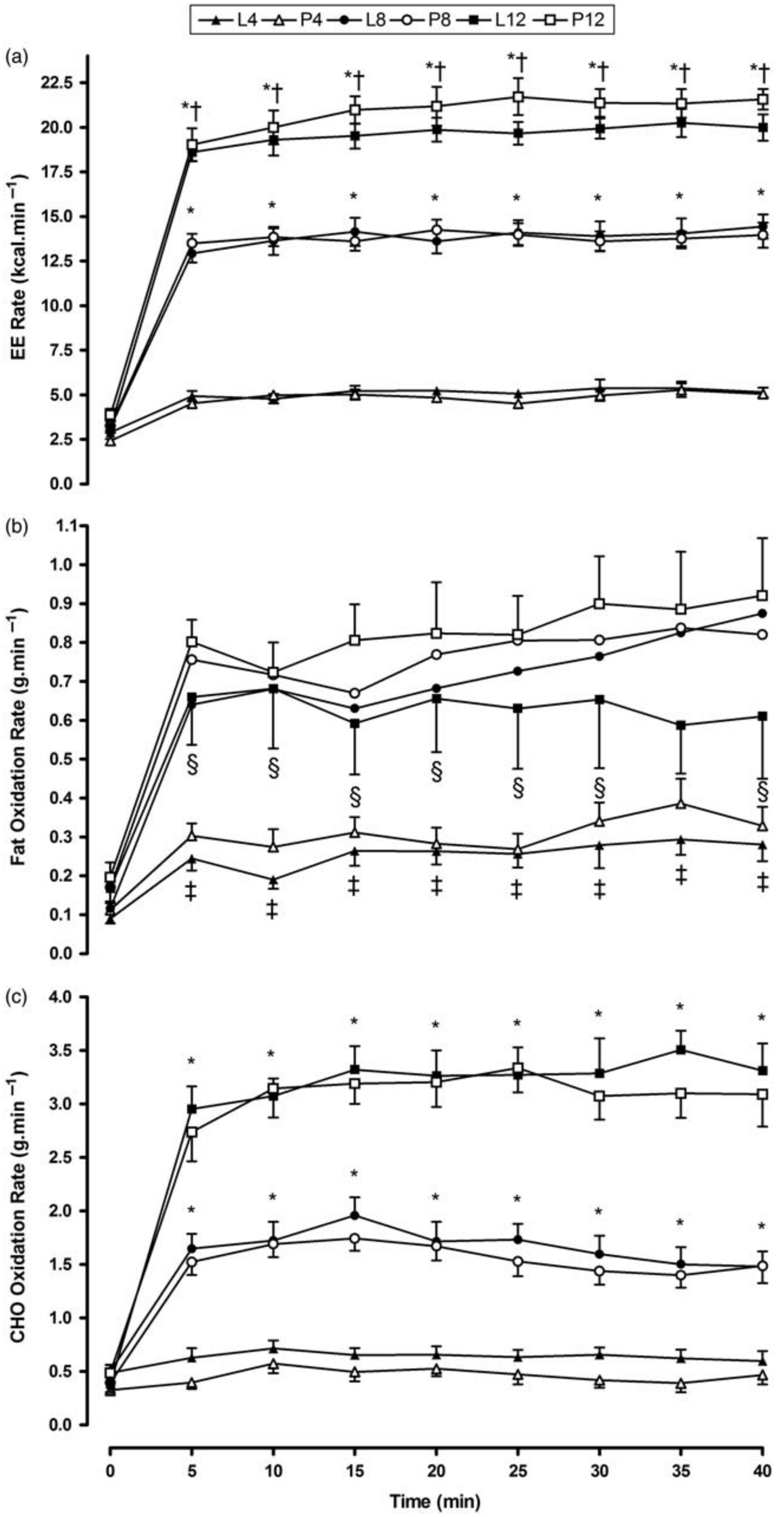

Figure 1. Substrate oxidation and EE responses to speed and portable gas analyser carriage: '*' denotes a significantly greater response than at the slower speeds ($p < 0.001$); '†' denotes a significant increase in EE during P ($p < 0.05$); '§' denotes a significantly lower fat oxidation rate during L ($p < 0.05$); '‡' denotes a significantly lower fat oxidation rate than the faster trials ($p < 0.05$).

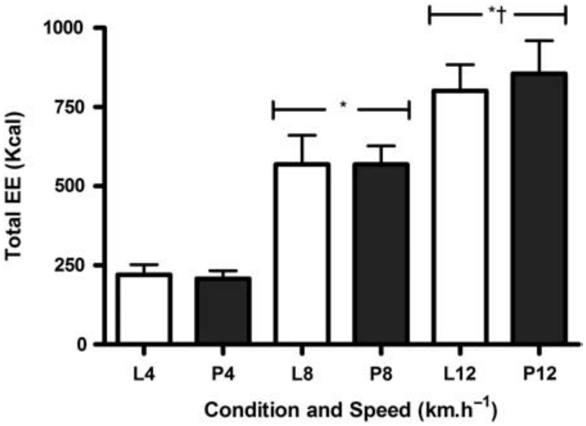

Figure 2. Total EE for each trial: '*' denotes a significantly greater EE than the slower speeds ($p < 0.001$); '†' denotes a significantly higher EE due to load carriage ($p < 0.05$).

The oxygen cost ($\dot{V}O_2$) closely reflected the EE responses particularly at 8 and 12 km h^{-1} [Figure 3(a)]; in each case, these speeds produced significantly greater $\dot{V}O_2$ than the lowest speed ($p < 0.001$)]. During the course of the trials at both 4 and 8 km h^{-1}, there were no alterations to $\dot{V}O_2$ from 5 to 40 min ($p = 1.000$ and 0.187, respectively). At 12 km h^{-1}, carriage of the gas analyser caused a significant elevation in $\dot{V}O_2$ ($p = 0.005$) which continued to increase throughout P12 ($p = 0.021$) but not during L12 ($p = 0.102$). HR, RPE (Table 1) and perceived effort (Figure 4) showed no load carriage-related differences whilst undertaking these tasks ($p > 0.05$), but each variable responded in proportion to the speed requirement of the trials ($p < 0.01$).

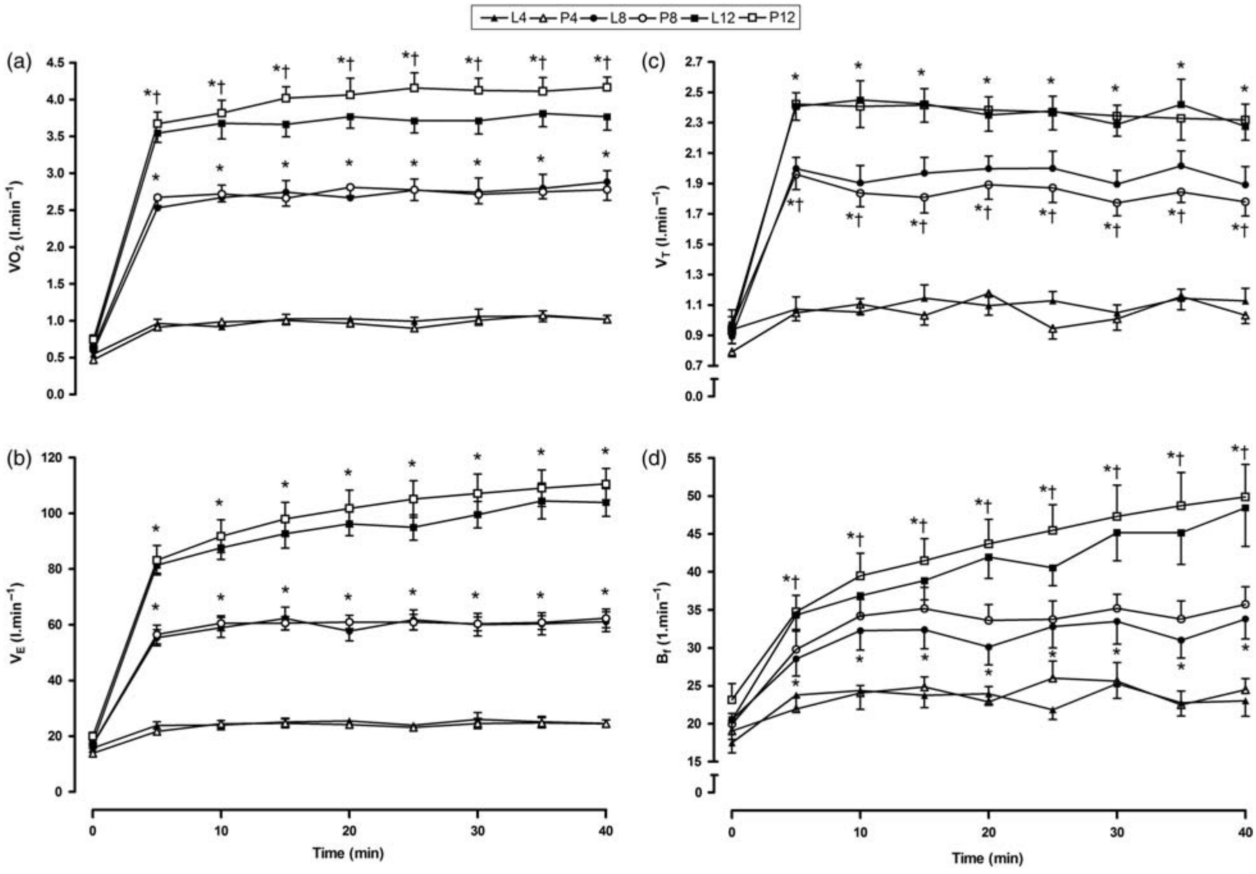

Figure 3. Respiratory responses to speed and portable gas analyser carriage: '*' denotes a significantly greater response than at the slower speeds ($p < 0.01$); '†' denotes a significant difference between P and L trials ($p < 0.05$).

Table 1. Physiological and exertion responses to speed and portable gas analyser carriage.

Condition	HR ($\mathrm{b\,min^{-1}}$)	RPE (AU)
L4	74.4 ± 6.4	6.6 ± 0.5
P4	74.6 ± 9.1	6.4 ± 0.5
L8	125.2 ± 19.8*	9.7 ± 1.7*
P8	123.6 ± 18.2*	8.8 ± 1.9*
L12	160.6 ± 23.5**	13.8 ± 2.7**
P12	160.2 ± 28.0**	13.0 ± 3.3**

*Significant difference compared to the lower speed ($p < 0.01$). **Significant difference compared to both the lower speeds ($p < 0.01$).

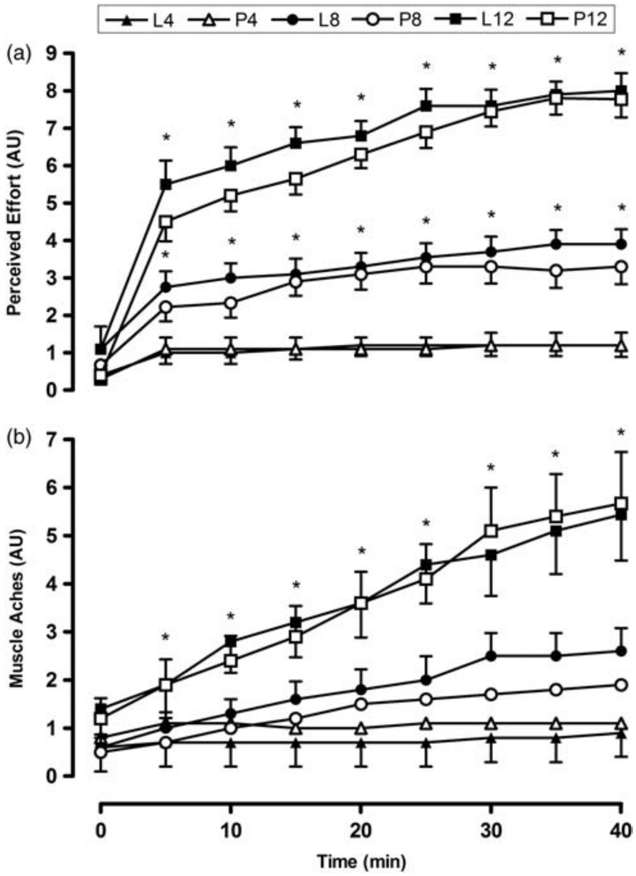

Figure 4. Subjective ratings of effort and muscle soreness: '*' denotes a significantly greater rating than at the slower speeds ($p < 0.05$).

4. Discussion

The primary purpose of this study was to investigate the energy costs of portable gas analyser carriage at a range of intensities during prolonged treadmill exercise. In order to do this, we assessed a variety of physiological and subjective indices of effort in response to the continuous protocol. Recently, Sparks, Orme, and McNaughton (2013) investigated the cost of gas analyser carriage during a short duration incremental treadmill running protocol and reported increases in EE of 3.95–7.02% at 7 and 14 $\mathrm{km\,h^{-1}}$, respectively. We therefore used an exercise protocol of 40 min at a variety of constant speeds, with a similar participant population in order to establish the effects of gas analyser carriage on more prolonged ambulation. This study presents novel data that suggest that the use of portable gas analysis systems during locomotion increases total EE by ~6.7% (range 0.52–17.9%) for 40 min of running at 12 $\mathrm{km\,h^{-1}}$, which equates to 10.05% additional cost per hour. Interestingly, there were no effects of gas analyser carriage during walking or light running, which suggests that this type of load is not large enough to cause additional energy requirements when activity intensity is light (4 $\mathrm{km\,h^{-1}}$) to moderate (8 $\mathrm{km\,h^{-1}}$). We attempted to assess the effects of additional load carriage on the multi-faceted nature of exertion (Hutchinson and Tenenbaum 2006), and it was interesting to note that there was no effect of this extra load on either the physical perceptions of exertion or the physical effort employed in the task. This was in spite of increases in EE related to intensity and concurrent speed-related increases in perceived ratings of effort. This suggests that such an additional load has no effect on the relative salience physiological feedback from the periphery (muscle aches) or on the cognitive appraisals of the task (effort).

In the case of all the measured variables, with the exception of fat oxidation, the magnitude of the observed response was in proportion to the speed/intensity requirement (Foissac et al. 2009) and therefore the energy demand of the trials (Sparks, Orme, and McNaughton 2013; Lloyd and Cooke 2000; Hong et al. 2000). Elevated energy, and therefore oxygen cost, in the P12 trial was the result of increased contributions from fat oxidation and resulted in an interaction effect in this trial. This was in the absence of a concomitant elevation in CHO oxidation and is likely to be the result of the postural changes that occur during load carriage (Singh and Koh 2009), which have been shown to increase the activation of the upper leg and the lower back muscles during this type of activity (Cook and Neumann 1987). The elevated cost caused no alterations to V_{T} but B_{f} was increased; there is no indication to suggest that this was a result of the wearing of the harness, since any restrictive effect would reduce V_{T} and increase B_{f}. Similar responses to these have also been observed during marching for comparable durations, where additional loads were carried (Quesada et al. 2000). Interestingly, V_{T} was elevated in P8 more than in L8 but this did not result in elevated V_{E}, presumably because B_{f} tended to be lower (although not significantly) in L8. The reasons for this are unclear, given that there were no differences in energy cost or substrate oxidation at 8 km h^{-1}. Previous work by Knapik, Reynolds, and Harman (2004) has suggested that performance decreases between 1% and 3% for each kilogram of load. These data, however, have been derived from work in military settings where the typical loads are much higher and the speeds are very low. It is currently unclear what effects the observed additional energy costs have on exercise performance.

This study represents the first attempt to quantify the effects of gas analyser carriage in a controlled environment, while exercise was performed on a treadmill at pre-determined speeds for a prolonged period. Whilst this is an obvious and necessary first step in the determination of the costs of such activities, this is a limitation to this study, since locomotion taking place in the field is likely to be subject to variations in speed as a result of the terrain over which participants are moving. The addition of gradient alterations, particularly uphill terrain, is likely to exacerbate the effects of additional weight carriage (Knapik, Reynolds, and Harman 2004; Lloyd and Cooke 2000), and as a consequence, future studies should focus on the quantification of energy costs associated with gas analyser carriage over a wider variety of terrain. Furthermore, future work should also consider the effects of this type of light load carriage, in respect to sport and exercise performance rather than prescriptive protocols with pre-determined intensities.

5. Conclusion

Portable gas analysis systems have been shown to provide valid and reliable respiratory data during a variety of exercise modalities, but it is clear that their carriage increases the cost of weight-baring activities such as running. Therefore, researchers using such equipment for the determination of the respiratory responses to exercise should be aware that their use may cause an additional energy requirement when running speed is high, but has no effect when exercise intensity is light. When running is found at speeds of ~12 km h^{-1}, there are considerable additional energy requirements of ~6.7%. Researchers should therefore preferentially use laboratory-based gas analysis systems that do not require carriage. Whilst these systems are designed to measure the effects of exercise on the costs of such activities, their carriage increases the energy demands of running exercise but does not alter effort perception during this time.

Notes

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