©Journal of Sports Science and Medicine (2010) **9**, 332-337
http://www.jssm.org

Research article

Cycling efficiency in trained male and female competitive cyclists

James Hopker [1]✉, Simon Jobson [1], Helen Carter [2] and Louis Passfield [1]
[1] Centre for Sports Studies, University of Kent, Chatham Maritime, Chatham, Kent UK, [2] Chelsea School, University of Brighton, Brighton, West Sussex, UK

Abstract
The aim of this study was to examine differences in cycling efficiency between competitive male and female cyclists. Thirteen trained male (mean ± SD: 34 ± 8 yr, 74.1 ± 6.0 kg, Maximum Aerobic Power (MAP) 414 ± 40 W, VO_{2max} 61.3 ± 5.4 ml·kg^{-1}·min^{-1}) and 13 trained female (34 ± 9 yr, 60.1 ± 5.2 kg, MAP 293 ± 22 W, VO_{2max} 48.9 ± 6.1 ml·kg^{-1}·min^{-1}) competitive cyclists completed a cycling test to ascertain their gross efficiency (GE). Leg and lean leg volume of all cyclists was also measured. Calculated GE was significantly higher in female cyclists at 150W (22.5 ± 2.1 vs 19.9 ± 1.8%; $p < 0.01$) and 180W (22.3 ± 1.8 vs 20.4 ± 1.5%; $p = 0.01$). Cadence was not significantly different between the groups (88 ± 6 vs 91 ± 5 rev·min^{-1}). Lean leg volume was significantly lower for female cyclists (4.04 ± 0.5 vs 5.51 ± 0.8 dm^3; $p < 0.01$) and was inversely related to GE in both groups at 150 and 180W ($r = -0.59$ and -0.58; $p < 0.05$). Lean leg volume was shown to account for the differences in GE between the males and females. During an "unloaded" pedalling condition, male cyclists had a significantly higher O_2 cost than female cyclists (1.0 ± 0.1 vs 0.7 ± 0.1 L·min^{-1}; $p < 0.01$), indicative of a greater non-propulsive cost of cycling. These results suggest that differences in efficiency between trained male and female cyclists can be partly accounted for by sex-specific variation in lean leg volume.

Key words: Gross efficiency, endurance performance, sex-related differences, power output, leg volume.

Introduction

Whilst there is growing research interest in female cycling (Ashenden et al., 1999), to our knowledge the effect that sex differences have on efficiency remains to be investigated in competitive cyclists. Most studies have involved only male participants, with, for example, comparisons being made between trained and untrained riders (Hopker et al., 2007; Hopker et al., 2009). Yasuda et al. (2008) investigated differences between untrained males and females during arm and leg exercise. They found no significant sex differences in GE, delta efficiency, the ratio of the change in work accomplished or the change in energy expended (Faria et al., 1982) at relative exercise intensities 70-115% of ventilatory threshold. Whipp and Wasserman (1972) have shown this approach to measuring efficiency to be problematic as exercise at or above lactate/ventilatory thresholds incurs additional VO_2 due to the slow component of VO_2 kinetics, thereby potentially causing erroneous efficiency values.

It has been suggested that gross efficiency (GE) [defined as the ratio of work accomplished to energy expended (Gaesser and Brooks, 1975)] is one of the most important functional abilities of a cyclist (Coyle, 1995) as it determines the amount of power that can be produced for a given O_2 cost and level of energy expenditure. Other methods of calculating efficiency using base-line subtractions (i.e. Net, Work and Delta Efficiency), have all been suggested to be conceptually flawed. For a review see Ettema and Loras (2009). It is, therefore, most appropriate to focus on GE as the primary outcome variable as a measure of the efficiency of whole body exercise. Horowitz et al. (1994) demonstrated that cyclists with a high GE were able to generate a greater power output for the same VO_2 than riders possessing a lower GE. Similarly Lucia et al. (1998) found that professional riders were able to generate a greater power output than amateurs even though their VO_{2max} values were similar. There are a number of factors which have been shown to affect GE in cycling: cadence (Chavarren et al., 1999; Coast et al., 1986; Samozino et al., 2006), body mass (Berry et al., 1993), cycling position (Browning et al., 1992; Gonzales and Hull, 1989), pedalling technique (Kautz and Neptune, 2002; Korff et al., 2007), prior exercise (Passfield and Doust, 2000), muscle fibre type (Coyle et al., 1992), and training status (Hopker et al., 2007; 2009; 2010).

Studies investigating differences between males and females in running economy have produced equivocal findings (Billat et al., 2003; Bransford and Howley, 1979; Davies and Thompson, 1979; Daniels and Daniels, 1992; Joyner, 1993; Maughan and Leiper, 1983). This may, in part, reflect the calibre of the sample populations used. Differences in running economy between sexes in some study populations appear smaller than the intra-individual variation among individual runners (Saunders et al., 2004). On closer analysis of much of this research, it appears that body/limb mass differences could account for a large proportion of any differences found between the sexes. Indeed, Berry et al. (1993) have demonstrated that efficiency during cycling is negatively correlated with body mass over a range of power outputs and cadences in female cyclists. Similarly, Francescato et al. (1995) found that artificially increasing leg mass by the addition of weights strapped to the thighs and lower legs resulted in a significantly higher oxygen cost of cycling across a range of pedal cadences.

To the authors' knowledge, no study has investigated differences in GE between male and female trained competitive cyclists using work rates that are representative of those commonly used during training and racing. Therefore, the aim of the present study was to establish whether gross efficiency differs between trained male and female competitive cyclists. A secondary aim was to

Received: 03 March 2010 / Accepted: 12 April 2010 / Published (online): 01 June 2010

identify if differences in leg volume could account for any differences found in efficiency between the sexes.

Methods

A cross-sectional study design was utilized. Twenty six competitive cyclists of regional and national standard were recruited, comprising 13 males (mean ± SD: age 34 ± 8 yr, mass 74.1 ± 6.0 kg, Maximum Aerobic Power (MAP) 414 ± 40 W, VO_{2max} 61.3 ± 5.4 $ml \cdot kg^{-1} \cdot min^{-1}$) and 13 females (34 ± 9 yr, 60.1 ± 5.2 kg, MAP 293 ± 22 W, VO_{2max} 48.9 ± 6.1 $ml \cdot kg^{-1} \cdot min^{-1}$), both with at least 2 years of cycle training/racing experience. Adequate participant numbers were estimated using *a priori* statistical power analysis (Hopker et al., 2007). Prior to testing, each cyclist gave written informed consent for this study which had university ethics committee approval. Before participating in the exercise trials, participants underwent habituation sessions in order to familiarise themselves with the testing procedures. The cyclists were instructed not to train in the 24 hours before testing. The female participants performed their tests in the early-follicular phase of the menstrual cycle to standardise hormonal effects influencing metabolic responses (Gurd et al., 2007; Janse de Jonge, 2003). Testing of all participants was conducted during the competitive phase of the season as we have previously shown GE to be highest during this period (Hopker et al., 2009).

Each rider attended the laboratory for a test of cycling efficiency and maximal aerobic power. Upon reporting to the laboratory, body mass was measured to the nearest 0.1 kg using a beam balance scales (Seca, Germany). A stadiometer (Seca, Germany) was used to measure stature to the nearest 0.5 cm. Lower limb dimensions and skin fold thicknesses were measured prior to each cyclist's test to enable the calculation of total and lean leg volume according to the procedures of Winter et al. (1991). Specifically, leg volume was estimated using limb circumference measurements to calculate the volume (v) of a truncated cone:

$$v = 1/3\ h\ (a + \sqrt{ab} + b)$$

where a and b are the areas of two parallel surfaces derived from circumference measurements, and h is the distance between the surfaces.

Lean leg volume was subsequently calculated by subtracting the estimated subcutaneous fat measurements from the leg diameter measurements prior to calculation of lean leg volume.

Throughout each trial, laboratory conditions were held constant (ambient temperature 18-22°C, relative humidity 45-55%) and participants were cooled using an electric fan.

The cyclists rode an electronically braked ergometer (Lode Excalibur Sport, Lode, Groningen, NL) which was calibrated before the start of the study for power outputs of 25-1000 W at cadences of 40, 60, 80, 100 and 120 $rev \cdot min^{-1}$ and was found to be within 1% of a true value (CV = 1%, CI = 0.7-1.2%). Each cyclist's bike setup (saddle height, distance between saddle and handle bars, handle bar height, crank lengths) was recorded and reproduced for all tests.

Cyclists completed a cycling efficiency test. After an 8-minute period of "unloaded" cycling (for the determination of an unloaded cycling O_2 cost), female cyclists started at a power output of 120W and males at a power output of 150W. In both groups, work rate increased by 30 W every 8 min until the measured concentration of lactate measured in fingertip blood samples (Biosen, EKF, Germany) reached 4 $mmol \cdot L^{-1}$. All cyclists used their preferred pedal cadence throughout ($rev \cdot min^{-1}$). During this test Lactate Threshold (LT) was determined as the power preceding 1 $mmol \cdot L^{-1}$ increase in blood lactate (Coyle, 1999) and OBLA (Onset of Blood Lactate Accumulation) as a measured 4 $mmol \cdot L^{-1}$ lactate concentration (Heck et al., 1985). The power at LT and OBLA was determined from interpolation. Once 4 $mmol \cdot L^{-1}$ was obtained and/or RER exceeded 1.00 the cycling efficiency test was terminated.

Expired gases were collected on a breath-by-breath basis (Quark b2, Cosmed, Italy) over the final three minutes of each 8-minute bout of exercise completed for the measurement of VO_2 and RER. Eight-minute stages were used for gas collection as Chuang et al. (1999) suggest that during early exercise CO_2 storage in the muscle decreases RER values. As a result CO_2 takes longer to reach steady state, ~4 minutes. CO_2 stability must be ensured prior to sampling due to its influence on RER which is used within the efficiency calculations.

Power output was measured and recorded at 1-second intervals. These data were used to calculate GE using the equation:

$$GE = \frac{\text{Work accomplished}}{\text{Energy expended}} \times 100\%$$

(Gaesser and Brooks, 1975)

Following the test to determine GE, participants rested for 5 minutes prior to the commencement of a ramp protocol to determine VO_{2max}. This protocol started at 150W using a 20W per minute ramp rate and continued until volitional exhaustion. VO_{2max} was determined as the highest measured 60 second VO_{2max} achieved during the incremental test. Maximal power output (MAP) was calculated as the average power output over the final minute of the ramp test.

Data analysis

Prior to all statistical analyses, normality of data were confirmed using a Shapiro-Wilk Test. Submaximal VO_2 data were averaged on a minute-by-minute basis and then analysed using an ANOVA to establish the potential influence of the "slow component" of VO_2kinetics. This was because of potential distortion of the linearity of the VO_2-work rate relationship due to additional VO_2consumption after the 3rd minute of supra-anaerobic threshold exercise (Whipp, 1972).

Comparisons of the mean GE between male and female cyclists were assessed using MANOVA. A MANOVA was used to account for both leg and lean leg volume as uncontrolled covariates influencing the relationship between GE and sex. Subsequently, differences between groups and across intensities were analysed using unadjusted post-hoc analysis (Least Significant Difference). Statistical significance was set at 95% confidence ($p < 0.05$). Differences in GE between the groups were assessed at 0, 150, 180 and 210W, as well as at intensities equivalent to LT and 60% MAP using interpolation from the steady state data. Differences in other descriptive physiological data between male and female cyclists were identified using independent student's t-tests. Relationships between efficiency and leg volumes were assessed using Pearson's correlation coefficient. Finally the estimated O_2 cost of "unloaded" cycling was calculated from the y-intercept of the relationship between work rate and O_2 uptake. All values are expressed as mean and standard deviation (mean ± SD) unless otherwise stated.

Results

Table 1 presents descriptive and physiological data for male and female cyclists.

All variables presented in Table 1 were significantly higher in male cyclists ($p < 0.01$) except maximum heart rate and preferred cadence ($p > 0.05$).

Table 1. Descriptive and physiological data for trained male and trained female cyclists. Data presented as mean (±SD).

	Male Cyclists	Female Cyclists
Mass (kg)	74.1 (6.0)	60.1 (5.2) *
MAP (W)	414 (40)	300 (24) *
VO_{2max} ($L·min^{-1}$)	4.6 (.5)	3.0 (.4) *
VO_{2max} ($mL·kg^{-1}·min^{-1}$)	61.3 (5.4)	48.9 (6.1) *
Lactate Threshold (W)	267 (25)	159 (14) *
OBLA (W)	305 (34)	200 (14) *
HR_{max} ($b·min^{-1}$)	184 (10)	185 (12)
Leg Volume (dm^3)	8.27 (1.2)	7.62 (1.4) *
Lean Leg Volume (dm^3)	5.51 (.8)	4.04 (.5) *
Preferred Cadence (rpm^{-1})	91 (5)	88 (6)

* significantly different to male riders ($p \leq 0.01$).

VO_2 at work rates of 150 and 180W showed no significant differences (mean difference <15.5mL·min^{-1}; $p = 0.93$) between the 3rd and 8th minutes of each exercise stage. However, female cyclists demonstrated a significant "slow component" above 210W. This data was therefore excluded from the subsequent analysis.

Lean leg volume was significantly higher in male cyclists and was inversely related to GE at 150 and 180 W in both male and female cyclists ($r = -0.59$ and $r = -0.58$; $p < 0.01$ respectively). Total leg volume was also higher in male cyclists, although no significant relationships were found with GE at either power output ($r = -0.35$ and $r = -0.36$ respectively; $p > 0.05$).

Results for GE at absolute and relative exercise intensities are provided in Table 2. VO_2 data for the male and female cyclists are shown in Figure 1. MANOVA analysis identified that female cyclists possessed a significantly higher GE than males across the common intensities of 150 and 180 W ($p < 0.01$). Including leg volume as a covariate did not alter the difference between groups (for both 150 and 180 W). However, the addition of lean leg volume as a covariate eliminated the GE differences between males and females at both work rates ($p = 0.08$ and $p = 0.43$ at 150 W and 180 W respectively).

Table 2. GE (%) for trained male and trained female cyclists at absolute power outputs of 150 and 180W and relative to LT and 60%MAP. Data presented as mean (±SD).

	150W	180W	LT	60%MAP
Female	22.5 (2.1) *	22.3 (1.8) *	23.2 (3.5)	23.5 (3.5)
Male	19.9 (1.8)	20.4 (1.5)	21.9 (1.7)	21.7 (1.6)

* significantly different to male value ($p < 0.05$).

Gross efficiency at intensities equivalent to LT and 60%MAP, was not different between male and female cyclists ($p = 0.30$ and $p = 0.07$ respectively). The addition of leg volume and lean leg volume as covariates did not alter this finding ($p > 0.05$).

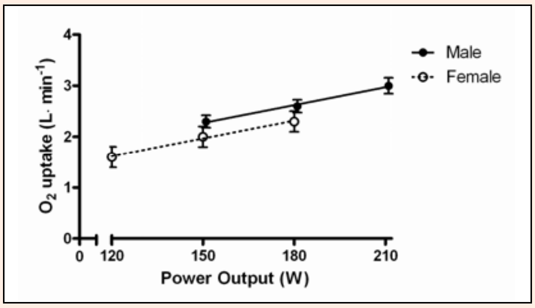

Figure 1. Oxygen uptake (L $O_2·min^{-1}$) plotted against the submaximal power output in trained male and trained female cyclists.

As leg volume accounted for the differences in efficiency values obtained for males and females, it seemed possible that the O_2 cost of unloaded cycling would be significantly different between groups. Oxygen uptake (L $O_2·min^{-1}$) was plotted against the submaximal power outputs used for male and female cyclists (see Figure 1). The corresponding intercept of this relationship is an estimate of the 'unloaded' O_2 cost of moving the legs, and hence an independent correlate of leg volume. Statistical analysis of the data demonstrated a significant difference in the y-intercept of the male and female regression lines ($p < 0.01$), with no difference in the slope of the two ($p = 0.99$). However, this predicted "unloaded" cost of cycling was significantly lower than the actual cost measured during the "unloaded" cycling phase of test in both males (0.64 vs 1.0 L·min^{-1}; $p < 0.01$) and females (0.20 vs 0.70 L·min^{-1}; $p < 0.01$). Nevertheless, the main conclusions were consistent, with male cyclists having a significantly higher VO_2 than females during "unloaded" pedalling (1.0 ± 0.1 vs 0.7 ± 0.1 L·min^{-1}; $p < 0.01$).

Discussion

The main finding of this study was that GE was significantly higher in female cyclists at each of the absolute power outputs measured. No difference was found in relative values, although female data tended to be higher (~23.5% vs ~21.9%). When lean leg volume was factored into the analysis as a covariate, significant differences in GE between trained male and female cyclists were no longer evident. Therefore, lean leg volume is unlikely to be the only explaining factor of the differences observed.

Gross efficiency has been suggested by Coyle (1999) to be an important determinant of endurance performance, combining with lactate threshold VO_2 to establish performance power output. The values reported in this study for male cyclists are similar to those reported previously (Coyle et al., 1992; Gaesser and Brooks, 1975; Hopker et al., 2007; 2009; Horowitz et al., 1994). We are not aware of any previous efficiency values reported for female competitive cyclists. The difference in GE seen between the sexes in the current study is greater than we have previously found for the variation (in males) over the course of a competitive cycling season (Hopker et al., 2009). More specifically, the current study demonstrates a 2.2% difference between males and females compared to a ~1% change over the course of a season (Hopker et al., 2009). Therefore, the difference between the sexes is greater than any seasonal variation that could be expected within any one cyclist's efficiency. However, these differences only appear at the absolute work rates used.

It could be suggested that work rate is a key factor in explaining the differences observed between male and female cyclists. Specifically, female cyclists used absolute power outputs that were lower than male cyclists. This might have influenced the GE values obtained and could, in part, account for the differences seen between the groups. When cycling at the same relative intensities no significant differences in GE between trained males and females were found. However, it is interesting to note that the mean difference in GE between male and female cyclists at 60%MAP was 1.8% (males: 21.7 ± 1.6 vs females: 23.5 ± 3.5%). Statistical significance of $p = 0.07$ suggests no difference between the groups. Although, post hoc analysis shows this may be an issue of insufficient statistical power within the method to detect a difference ($1-\beta = 0.35$).

Some studies have found that increasing pedalling cadence decreases GE (Chavarren and Calbet, 1999; Faria et al., 1982), although not in professional cyclists (Lucia et al., 2004). In the current study there were no significant differences in cadence between the sexes.

Although the physiological and metabolic determinants of GE remain to be fully understood, several factors could be responsible. GE has been suggested to be a good indicator of whole body efficiency rather than being specifically related to that of the exercising muscle (Coyle et al., 1992; Gaesser and Brooks, 1975). This may account for part of the differences seen. Females tend to have a higher percentage of body fat and a lower percentage of lean tissue mass compared to males (Lewis et al., 1986). As fat tissue has a lower metabolic activity than muscle per unit mass, female basal metabolic rate averages 5 to 10% lower than men (Ravussin et al., 1986). Therefore, females have a lower proportion of the total energy expenditure from non-contributory (i.e. resting) metabolism. This would mean that females appear more efficient at lower exercise intensities where the impact of this non-contributory metabolism is greater (Gaesser and Brooks, 1975).

The findings of this study support those of other authors (Francescato et al., 1995; Neder et al., 2000; Pate et al., 1992) in suggesting that individuals with a greater proportion of mass in the legs require more energy and thus oxygen to move their legs during running and cycling exercise. Accordingly, it may be expected that, when generating the same power output, the absolute cost of exercise is higher for trained male cyclists as both their leg volumes and lean leg volumes were significantly greater than the trained female group. Interestingly, the use of lean leg volume as a covariate within the analysis of this study served to negate the significant difference in GE between the two groups. Thus it would appear that lean leg volume is able to account for the differences observed in GE, rather than differences in any physiological parameter. The same effect was not seen when total leg volume was added as a covariate to the statistical analysis (i.e., the significant difference between the two groups remained). This suggests that lean leg volume influences GE to a greater extent than total leg volume.

As male cyclists have a larger limb segment mass they may conserve momentum better than their female counterparts or, more likely, they have greater rotating leg mass. However, when considering the oxygen cost of "unloaded" cycling, as predicted by the intercept of the O_2 cost-power output relationship (see Figure 1), males have a significantly higher VO_2. This would tend to suggest that leg volume/mass is an important determinant of the observed differences in oxygen cost and therefore GE.

The results of measuring the actual O_2 cost during an "unloaded" pedalling condition confirm those of the predicted cost from the y-intercept of the VO_2-power relationship and are in agreement with data previously published (Hintzy-Cloutier et al., 2003; Sidossis et al., 1992). Interestingly, however, there was a significant difference upon comparison of the two methods of determining the O_2 cost of "unloaded" pedalling. For both trained male and female cyclists the y-intercept prediction significantly underestimated the actual O_2 cost recorded during the actual "unloaded" pedalling condition.

Conclusion

In conclusion, we have demonstrated that there are differences in GE between trained male and female cyclists at absolute work rates of 150 and 180W. However, when lean leg volume is accounted for these differences are no longer evident. This might be because the whole-body GE calculation also includes the higher oxygen cost incurred by male cyclists during "unloaded" cycling. In addition to work rate, lean leg volume may therefore be an important factor to consider when investigating sex-related differences in physical fitness, energy expenditure and efficiency in male and female trained cyclists. Further work is required to fully elucidate those factors which determine GE.

References

Ashenden, M., Gore, C., Martin, D., Dobson, G.P. and Hahn, A.G. (1999) Effects of a 12 day 'live high, train low' camp on reticulocyte production and haemoglobin mass in elite female road cyclists. *European Journal of Applied Physiology* **80,** 472-478.

Berry, M., Storsteen, J. and Woodard, M. (1993) Effects of body mass on exercise efficiency and VO_2 during steady state cycling.

Medicine and Science in Sports and Exercise **25,** 1031-1037.

Billat, V., Lepretre, P., Heugas, A., Laurence, M.H., Salim, D. and Koralsztein, J.P. (2003) Training and bioenergetic characteristics in elite male and female Kenyan runners. *Medicine and Science in Sports and Exercise* **35,** 297-304.

Bransford, D. and Howley, E. (1979) Oxygen cost of running in trained and untrained men and women. *Medicine and Science in Sports and Exercise* **9,** 41-44.

Browning, R.C., Gregor, R.J. and Broker, J.P. (1992) Lower extremity kinetics in elite athletes in aerodynamic cycling positions [abstract]. *Medicine and Science in Sports and Exercise* **24,** S186.

Chavarren, J. and Calbet, J.A.L. (1999) Cycling efficiency and pedalling frequency in road cyclists. *European Journal of Applied Physiology* **80,** 555-563.

Chuang, M.L., Ting, H., Otsuka, T., Sun, X.G., Chiu, F.Y., Beaver, W.L., Hansen, J.E., Lewis, D.A. and Wasserman, K. (1999) Aerobically generated CO2 stored during early exercise. *Journal of Applied Physiology* **87,** 1048-1058.

Coast, J., Cox, R., and Welch, H. (1986) Optimal pedalling rate in prolonged bouts of cycle ergometry. *Medicine and Science in Sports and Exercise* **18,** 225-230.

Coyle, E.F. (1995) Integration of the physiological factors determining endurance performance ability. *Exercise and Sports Science Reviews* **23,** 25-64.

Coyle, E.F. (1999) Physiological determinants of endurance exercise performance. *Journal of Science and Medicine in Sport* **2,** 181-189.

Coyle, E.F., Martin, W.H., Ehsani, A.A., Hagberg, J.M., Bloomfield, S.A., Sinacore, D.R. and Holloszy, J.O. (1983) Blood lactate threshold in some well trained ischemic heart disease patients. *Journal of Applied Physiology* **54,** 18-23.

Coyle, E.F., Sidossis, L.S., Horowitz, J.F. and Beltz, J.D. (1992) Cycling efficiency is related to the percentage of Type I muscle fibres. *Medicine and Science in Sports and Exercise* **24,** 782-788.

Davies, C. and Thompson, M. (1979) Aerobic performance of female marathon and male ultramarathon athletes. *European Journal of Applied Physiology* **41,** 233-245.

Daniels, J. and Daniels, N. (1992) Running economy of elite male and elite female runners. *Medicine and Science in Sports and Exercise* **24,** 483-489.

Ettema, G. and Loras, W.L. (2009) Efficiency in cycling: A review. *European Journal of Applied Physiology* **106,** 1-14.

Faria, I.E., Sjojaard, G. and Bonde-Petersen, F. (1982) Oxygen cost during different pedalling speeds for constant power output. *Journal of Sports Medicine* **22**, 295-299.

Francescato, M.P., Girardis, M. and di Prampero, P.E. (1995) Oxygen cost of internal work. *European Journal of Applied Physiology* **72,** 51-57.

Gaesser, G.A. and Brooks, G.A. (1975) Muscular efficiency during steady-state exercise: effects of speed and work rate. *Journal of Applied Physiology* **38,** 1132-1139.

Gonzales, H. and Hull, M.L. (1989) Multivariable optimisation of pedalling rate and crank arm length in cycling. *Journal of Biomechanics* **22,** 1152-1161.

Gurd, B.J., Schied, J., Paterson, D.H. and Kowalchuk, J.M. (2007) O_2 uptake and muscle deoxygenation kinetics during the transition to moderate-intensity exercise in different phases of the menstrual cycle in young adult females. *European Journal of Applied Physiology* **101,** 321-330.

Heck, H., Mader, A., Mucke, S., Muller, R. and Hollmann, W. (1985) Justification of the 4 mmol.L lactate threshold. *International Journal of Sports Medicine* **6,** 117-130.

Hintzy-Cloutier, F., Zameziati, K. and Belli, A. (2003) Influence of the base-line determination on work efficiency during submaximal cycling.*Journal of Sports Medicine and Physical Fitness* **43,** 51-56.

Hopker, J.G., Coleman, D.C., Passfield, L. and Wiles, J. (2010) The effect of training volume and intensity on competitive cyclists' efficiency. *Applied Physiology, Nutrition and Metabolism* **35,** 17-22.

Hopker, J.G., Coleman, D.C. and Passfield, L. (2009) Changes in cycling efficiency during a competitive season. *Medicine and Science in Sports and Exercise* **41,** 912-919.

Hopker, J.G., Coleman, D.C. and Wiles, J.D. (2007) Differences in efficiency between trained and recreational cyclists. *Applied Physiology, Nutrition and Metabolism* **32,** 1036-1042.

Horowitz, J.F., Sidossis, L.S. and Coyle, E.F. (1994) High efficiency of type I muscle fibres improves performance. *International Journal of Sports Medicine* **15,** 152-157.

Janse de Jonge, X. (2003) Effects of the menstrual cycle on exercise performance. *Sports Medicine* **33,** 833-851.

Joyner, M.J. (1993) Physiological limiting factors and distance running: influence of sex and age on record performances. *Exercise and Sports Science Reviews* **21,** 103-133.

Kautz, S.A. and Neptune, R.R. (2002) Biomechanical determinants of pedalling energetic: Internal and external works are not independent. *Exercise and Sports Science Reviews* **30,** 159-165.

Korff, T., Romer, L.M., Mayhew, I. and Martin, J.C. (2007) Effect of pedalling technique on mechanical effectiveness. *Medicine and Science in Sports and Exercise* **39,** 991-995.

Lewis, D.A., Kamon, E. and Hodgson, J.L. (1986) Physiological differences between sexes. Implications for sports conditioning. *Sports Medicine* **3,** 357-369.

Lucia, A., Pardo, J., Durantez, A., Hoyos, J. and Chicharro JL. (1998) Physiological differences between professional and elite road cyclists. *International Journal of Sports Medicine* **19,** 342-348.

Lucia, A., San Juan, A., Montilla, M., GaNete, S., Santalla, A., Earnest, C. and Perez, M. (2004) In professional road cyclists, low pedalling cadences are less efficient. *Medicine and Science in Sports and Exercise* **36**:,1048-1054.

Maughan, R. and Leiper, J. (1983) Aerobic capacity and fractional utilization of aerobic capacity in elite and non-elite male and female marathon runners. *European Journal of Applied Physiology* **52,** 80-87.

Moseley, L., Achten, J., Martin, J.C. and Jeukendrup, A.E. (2004) No differences in cycling efficiency between world-class and recreational cyclists. *International Journal of Sports Medicine* **25,** 374-379.

Neder, J.A., Nery, L.E., Andreoni, S., Sachs, A. and Whipp, B.J. (2000) Oxygen cost for cycling as related to leg mass in males and females, aged 20 to 80. *International Journal of Sports Medicine* **21,** 263-269.

Passfield, L. and Doust, J.H. (2000) Changes in cycling efficiency and performance after endurance exercise. *Medicine and Science in Sports and Exercise* **32,** 1935-1941.

Pate, R.R., Macera, C.A., Bailey, S.P., Bartoli, W.P. and Powell, K.E. (1992) Physiological, anthropometric, and training correlates of running economy. *Medicine and Science in Sports and Exercise* **24,** 1128-1133.

Ravussin, E., Lillioja, S., Anderson, T.E., Christin, L. and Bogardus, C. (1986) Determinants of 24-hour energy expenditure in man. *Journal of Clinical Investigations* **78,** 1568-1578.

Samozino, P., Horvais, N. and Hintzy, F. (2006) Interactions between cadence and power output effects on mechanical efficiency during sub maximal cycling exercises. *European Journal of Applied Physiology* **97,** 133-139.

Saunders, P.O., Pyne, D.B., Telford, R.D. and Hawley, J.A. (2004) Reliability and variability of running economy in elite distance runners. *Medicine and Science in Sports and Exercise* **11,** 1972-1976.

Sidossis, L.S., Horowitz, J.F. and Coyle, E.F. (1992) Load and velocity of contraction influences gross and delta mechanical efficiency. *International Journal of Sports Medicine* **13,** 407-411.

Whipp, B.J. and Wasserman, K. (1972) Oxygen uptake kinetics for various intensities of constant-load work. *Journal of Applied Physiology* **33,** 351-356.

Winter, E.M., Brookes, F.B.C. and Hamley, E.J. (1991) Maximal exercise performance and lean leg volume in men and women. *Journal of Sports Sciences* **9,** 3-13.

Yasuda, N., Gaskill, S.E. and Ruby, B.C. (2008) No sex-specific differences in mechanical efficiency during arm or leg exercise relative to ventilatory threshold. *Scandinavian Journal of Medicine and Science in Sports* **18,** 205-212.

Key points

- Differences in GE exist between male and female cyclists.
- Males have a higher oxygen cost of "unloaded" cycling, as predicted by the intercept of the O_2 cost-power output relationship
- This suggests that in addition to work rate, leg volume/mass may be an important determinant of observed differences in oxygen cost and therefore GE, between male and female competitive cyclists.

AUTHORS BIOGRAPHY

James HOPKER
Employment
Lecturer, Centre for Sports Studies, University of Kent, UK.
Degree
PhD
Research interests
Exercise physiology, the effect of training and training status on exercise efficiency.
E-mail: j.g.hopker@kent.ac.uk

Simon JOBSON
Employment
Research Fellow, Centre for Sports Studies, University of Kent, UK.
Degree
PhD
Research interests
Cycling performance / physiology; mathematical modelling of athletic training and performance.
E-mail: S.A.Jobson@kent.ac.uk

Helen CARTER
Employment
Senior Research Fellow, Chelsea School, University of Brighton, UK.
Degree
PhD
Research interests
Cycling performance/physiology, critical power, oxygen uptake kinetics
E-mail: H.Carter@brighton.ac.uk

Louis PASSFIELD
Employment
Head of Centre, Centre for Sports Studies, University of Kent, UK.
Degree
PhD
Research interests
Cycling performance / physiology; mathematical modelling of athletic training and performance.
E-mail: L.Passfield@kent.ac.uk

✉ **James Hopker**
Centre for Sports Studies, University of Kent, Chatham Maritime, Chatham, Kent, ME4 4AG, UK