**THE EFFECT OF THE MENSTRUAL CYCLE ON RUNNING ECONOMY**

**HEAD TITLE:** MENSTRUAL CYCLE AND ECONOMY

ESTHER GOLDSMITH1\* & MARK GLAISTER1.

1Faculty of Sport, Health, and Applied Sciences, St Mary’s University, Strawberry Hill, Twickenham, UK.

**\*Corresponding Author**:

Esther Goldsmith

Faculty of Sport, Health, and Applied Sciences

St. Mary’s University

Waldegrave Road

Strawberry Hill

Twickenham, UK

TW1 4SX

Tel: (+44)208 240 4012

E-mail: esther.goldsmith@stmarys.ac.uk

**ABSTRACT**

BACKGROUND: The aim of this study was to examine the effect of the menstrual cycle on running economy (RE). METHODS:Using a repeated-measures design, ten eumenorrheic, trained female runners (age: 32 ± 6 yrs, V̇O2max: 59.7 ± 4.7 mL·kg-1·min-1) completed four, weekly, identical sub-maximal and maximal incremental step tests on a treadmill to measure physiological responses across a full menstrual cycle. For phase comparison, the results from the trials that fell in the early follicular (low oestrogen, low progesterone), late follicular (high oestrogen, low progesterone) and mid-luteal (high oestrogen, high progesterone) phases were used. RESULTS:There was a significant effect of menstrual cycle phase on RE (*p* = 0.001), withRE in the mid-luteal (ML) phase being worse than that of the early follicular (EF) (+2.33 mL.kg-1.min-1; *p* = 0.026) and late follicular (LF) (+2.17 mL.kg-1.min-1; *p* = 0.011) phases. The ML phase also resulted in elevated core temperature versus the EF (+0.51ºC; *p* = 0.001) and LF (+0.66ºC; *p* = 0.037) phases, and elevated minute ventilation versus the EF phase (+3.83 L.min-1; *p* = 0.003). No significant effects of menstrual cycle phase were found on body mass, heart rate, ratings of perceived exertion, time-to-exhaustion, maximal oxygen consumption, or blood lactate concentration. CONCLUSIONS:In the ML phase, which causes increased core temperature and minute ventilation, RE is impaired at exercise intensities that are applicable to training and performance. In physiologically stressful environments, this impairment in RE may have a significant impact on training and performance.

**Keywords**: Endurance; hormones; female athlete; efficiency

**INTRODUCTION**

Progesterone and oestrogen levels are in continual fluctuation in eumenorrheic, pre-menopausal women as a result of the menstrual cycle. Whilst primarily responsible for driving reproduction, progesterone and oestrogen travel in the bloodstream and bind to hormone receptors in the cardiovascular system, kidney tubules,1 and the hypothalamus.2 Therefore, oestrogen and progesterone can influence the cardiovascular, thermoregulatory and lymphatic systems, with the corresponding potential to affect exercise performance.3

The menstrual cycle can be split into 3 - 4 phases, characterised by changes in progesterone and oestrogen concentrations. However, there is a lack of consistency as to which days in the cycle the various phases occur.3 The majority of studies have tested participants twice in the cycle.5-10 However, there are three times in which hormone concentrations may particularly affect physiological and psychological functions3. These are: menstruation/early follicular (EF) phase, when progesterone and oestrogen are low; the late-follicular (LF) phase, when progesterone is low and oestrogen is high; and the mid-luteal (ML) phase, when both progesterone and oestrogen are high.

Running economy (RE) is defined as oxygen consumption (V̇O2) at a given, submaximal, steady-state velocity.11 An increase in V̇O2 signifies a decrease in RE, a potential impairment of running performance, and an increase in injury susceptibility.12 One factor that can influence V̇O2, and therefore RE, during exercise, is an elevation in core temperature (TC), which results in increased thermoregulatory and cardiovascular strain, increased metabolic demand, and decreased efficiency of oxidative phosphorylation.12 Indeed, an increase in TC of 1°C has been shown to impair RE by 6.4%.13 During the ML phase of the menstrual cycle, TC, is increased by 0.3 – 0.5°C17,18 as a result of high progesterone levels.19 During exercise, this increase in TC may be maintained6,8 which may be detrimental to RE. The ML phase has also been linked with increased minute ventilation (V̇E)9,10,17 and heart rate (HR) during exercise,6,8 likely due to the concomitant increased sympathetic activity.18

Impairments in RE of 3% have been observed in the ML phase compared with the EF phase, in association with increased V̇E.17 However, in the absence of TC measurements, the authors were unable to determine the effect of thermoregulatory strain on RE. Furthermore, whilst RE was calculated at speeds equating to 55% and 80% V̇O2max, menstrual cycle phase was only seen to affect RE at 80% V̇O2max. As such, the effects of the menstrual cycle on RE at a range of speeds that are applicable to training and competition are unclear. Therefore, the aim of this study was to investigate the effects of the menstrual cycle on RE at a range of speeds applicable to a trained athlete.

**MATERIALS AND METHODS**

**Experimental Overview**

All participants completed one familiarisation trial and four experimental trials under ambient temperature conditions of 20.5 ± 1.9ºC. Each experimental trial was 7 ± 1 days apart and occurred at the same time of day (± 1 hour) to minimise the influence of circadian rhythm on performance, body temperature, and hormone concentrations.All trials consisted of identical sub-maximal and maximal tests, performed on a motorised treadmill (H/P/ Cosmos Pulsar 4.0, H/P/Cosmos Sports & Medical GmbH, Nussdorf-Traunstein, Germany). Participants were instructed to abstain from caffeine, alcohol consumption, and vigorous exercise for 24 hours prior to each trial. Participants were instructed to record and repeat their food consumption for 12 hours before trials, and, as footwear can affect RE,19 to wear the same running shoes for each trial.For one menstrual cycle prior to, and for the duration of the experimental trials, participants completed a daily questionnairein order to monitor their training, menstrual cycle, and associated symptoms.

**Participants**

Ten eumenorrheic, trained female runners volunteered to participate in this study, which was approved by St Mary’s University Ethics Committee. Means ± standard deviation for age, height, body mass, and V̇O2max were: 32 ± 6 yrs, 1.69 ± 0.08 m, 58.4 ± 7.8 kg, and 59.7 ± 4.7 mL·kg-1·min-1 respectively. Eligibility was assessed using a study-specific menstrual cycle and training history questionnaire. Participants were deemed ‘trained’ if they ran ≥ 3 days*·*wk-1 for ≥ 1 yr and if they had a recent 10 km race time of ≤ 50 minutes. Eumenorrhea was defined as having a menstrual cycle of 28 ± 7 days, with 10 – 17 cycles in the past year.20 Females who had been pregnant in the last 6 months, were taking an hormonal contraceptive, were smokers, or had a history of cardiopulmonary disease were excluded from participation. Sample size was estimated from previous research in this area.17 Participants completed a participant readiness questionnaire and provided written informed consent before experimental procedures began.

**Procedures**

***Familiarisation Trial***

On reporting to the laboratory for the first time, body mass was measured, using portable scales (MPMS-230, Marsden Weighing Group, Oxfordshire, UK). Participants then completed a 5-minute self-paced warm-up on the treadmill and were fitted with a HR monitor (Polar, FT1, Polar Electro Oy, Kempele, Finland) and a face mask (Hans Rudolph, Kansas City, MO, USA), secured with a head-cap assembly (Hans Rudolph, Kansas City, MO, USA). Expired air was measured throughout all trials using an on-line gas analyser (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany) which was calibrated with known concentrations of oxygen and carbon dioxide. Participants then completed a submaximal incremental step test, which consisted of a series of 3-minute running stages, starting at a speed of 9 km·hr-1 and increasing by 1 km·hr-1 per stage until an end-stage blood lactate concentration ≥ 4 mmol·L-1 was obtained. The gradient of the treadmill was set at 1%, in order to simulate outdoor running.21 Rating of perceived exertion (RPE) was recorded at the end of each stage using a 15-point scale22, and mean HR was recorded in the final 15 s of each stage. Between each stage, participants stopped for 30 s, and a 20 µl capillary blood sample was obtained for subsequent analysis of blood lactate using an automated analyser (Biosen C line, EKF diagnostic GmbH, Barleben, Germany). After a 10-minute passive rest period, participants completed a second incremental test to establish their V̇O2max. Starting speed was 9 km·hr-1 and increased by 1 km·hr-1 every minute until volitional fatigue. On termination of the test, a capillary blood sample was obtained for lactate analysis (Lapeak); time-to-exhaustion (TTE) and HR at maximal workload (HRmax) were recorded also. V̇O2max was determined as the highest 30 s average V̇O2 recorded during the second incremental test provided that at least two of the following criteria had been met: 1) A plateau in V̇O2; as determined by an increase of less than 2 ml∙kg-1∙min-1 over the previous stage; 2) A respiratory exchange ratio ≥ 1.15; 3) A heart rate within 10 b∙min-1 of age predicted maximum; 4) A Lapeak ≥ 8 mmol∙L-1.

***Experimental Trials***

All experimental trials commenced by measuring body mass. Participants then rested for 10 minutes during which a 600 µl capillary blood sample was obtained from the ear lobe and collected in a lithium-heparin tube (Multivette; Starstedt AG & Co., Nümbrecht, Germany). The sample was immediately centrifuged (Ependorf centrifuge: Eppendorf UK Ltd, Histon, Cambridge, UK) for five minutes at 2000 g. Plasma samples were extracted subsequently and frozen at -80ºC until analysis of progesterone concentrations to confirm menstrual cycle phase. In-line with previous research,6,23,24 resting TC was measured aurally using an infrared thermometer (TH809 Infrared Ear Thermometer: Radiant Innovation Inc., Hsin Chu City, Taiwan), with the mean of three readings used in the subsequent analysis. Participants then completed the same two-part treadmill protocol as in the familiarisation trial.

***Menstrual Cycle Phase***

Menstrual cycle phase of each participant was determined using the information provided in the menstrual cycle history questionnaire in combination with the daily monitoring questionnaire. Ovulation was calculated as 14 days prior to the end of the cycle, as a normal luteal phase is 14.1 ± 1.4 days.25 The progesterone peak in the ML phase was thus defined as 7 - 9 days following ovulation estimation.26 It was then determined whether each trial was conducted in the EF Phase, LF Phase, or ML Phase. As each participant had a different menstrual cycle duration (29.3 ± 3.5 days), and therefore each testing session fell on a different day in relation to ovulation and menstruation, not all trials fell in a desired phase. Therefore, one trial was disregarded for each participant. Trials categorised as EF Phase were performed 2 ± 2 days from day 1 of each cycle; trials categorised as LF Phase were performed 4 ± 2 days prior to estimated ovulation; and trials categorised as ML Phase were performed 2 ± 1 days from the estimated progesterone peak. The phase of each trial was then confirmed with TC measurements, and progesterone analysis.

***Running Economy and Minute Ventilation***

RE was calculated for each trial using an average V̇O2 of the last 30 s of each stage completed by all participants in the sub-maximal incremental step test, and V̇E was also calculated in this way. The data was filtered to exclude breaths that were outside four standard deviations from the local 5-breath mean.32

***Blood Lactate***

Blood lactate responses to the sub-maximal step test were evaluated using Lactate-E software28 to determine the lactate threshold (LT) (determined from the log-log method)29 and the onset of blood lactate accumulation (OBLA) (running speed required to elicit a blood lactate concentration of 4 mmol·L-1).

**Statistical analyses**

All statistical analysis was performed using the Statistical Package for Social Sciences (SPSS Version 24, IBM, Armonk, USA). A Shapiro-Wilk test was used to confirm that no data violated assumptions of normality. A two-way repeated measures ANOVA was conducted to analyse the effects of menstrual cycle phase and treadmill running speed on RE, HR, V̇E, and RPE. The effect of menstrual cycle phase on plasma progesterone concentration, TC, V̇O2max, TTE, HRmax, LT, OBLA, and Lapeak, was evaluated using a one-way repeated measures ANOVA. If data was found to violate assumptions of sphericity, a Greenhouse-Geisser correction factor was used. Statistical significance was set at *p* < 0.05, and a Bonferroni adjustment was used for *post hoc* analyses.

**RESULTS**

**Plasma Progesterone Concentrations**

There was a significant effect of menstrual cycle phase on plasma progesterone concentration (*F*(1.03,9.30) = 9.5, *p* = 0.012), with values for the EF, LF, and ML phases being: 1.15 ± 1.35, 0.47 ± 0.45, and 10.29 ± 9.67 ng·mL-1, respectively. *Post hoc* analysis revealed that progesterone concentrations in the ML Phase were significantly higher than those of the EF Phase (mean difference: 9.14 ng·mL-1; 95% likely range: 0.19 – 18.09 ng·mL-1) and the LF Phase (mean difference: 9.82 ng·mL-1; 95% likely range: 0.76 – 18.88 ng·mL-1). In contrast, there was no significant difference in progesterone concentration between the EF and LF phases (*p* = 0.515).

**Core Temperature**

Measurements of TC for the EF, LF, and ML phases were: 35.94 ± 0.53ºC, 35.79 ± 0.65ºC and 36.46 ± 0.61ºC respectively. There was a significant effect of phase on TC (*F*(2,18) = 8.1, *p* = 0.003), with *post hoc* analysis showing that TC in ML Phase was significantly increased by an average of 0.51ºC (95% likely range: 0.23 to 0.79ºC, *p* = 0.001) compared with EF Phase, and by an average of 0.66ºC (95% likely range: 0.04 to 1.29ºC, *p* = 0.037) compared with LF Phase. There was no significant difference in TC between EF and LF phases.

**Body Mass**

Body mass in the EF, LF, and ML phases was 57.8 ± 7.9 kg, 57.8 ± 7.7 kg, and 57.7 ± 7.7 kg respectively. There was no significant effect of menstrual cycle phase on body mass (*F*(2,18) = 0.2, *p* = 0.818).

**Running Economy**

All participants achieved a running speed of at least 14 km·h-1 during the submaximal incremental step test; therefore, RE and V̇E were evaluated across all speeds from 9 – 14 km·h-1. RE results (measured as relative V̇O2) at each speed of the step test for each phase are shown in Figure 1. There was a significant effect of menstrual cycle phase on RE (*F*(2,18) = 9.8, *p* = 0.001) and of treadmill speed on RE (*F*(1.44,12.97) = 331.2, *p* < 0.001), but there was no significant interaction between menstrual cycle phase and treadmill speed (*F*(2.35,21.14) = 0.7, *p* = 0.695). *Post hoc* analyses revealed that RE was significantly impaired (V̇O2 was significantly increased) from EF to ML phases by 2.33 mL·kg-1·min-1 (95% likely range: 0.29 to 4.38 mL·kg-1·min-1, *p* = 0.026) and from LF to ML phases by 2.17 mL·kg-1·min-1 (95% confidence intervals: 0.53 to 3.81 mL·kg-1·min-1, *p* = 0.011). However, there was no significant difference in RE between EF and LF phases.

FIGURE 1. ABOUT HERE.

**Minute Ventilation**

Measures of V̇E at each speed of the step test for each phase of the menstrual cycle are shown in Figure 2. There was a significant effect of phase on V̇E (*F*(2,18) = 4.6, *p* = 0.025) and of treadmill speed/step-test stage on V̇E (*F*(1.33,11.97) = 182.6, *p* < 0.001). There was no significant phase x treadmill speed interaction (*F*(3.59,32.32) = 0.9, *p* = 0.458). *Post hoc* analysis revealed that V̇E was significantly increased in ML Phase compared with LF Phase by 3.71 L·min-1 (95% likely range: 0.67 to 6.75 L·min-1, *p* = 0.018). No significant differences were found between the EF and LF phase (*p* = 0.171) or between the EF and ML phases (*p* = 1.00).

FIGURE 2. ABOUT HERE.

**Heart Rate and Perceived Exertion**

HR and RPE responses during the step-test in each phase are shown in Tables 1 and 2. There was a significant effect of treadmill speed on HR (*F*(1.33,11.98) = 251.2, *p* < 0.001) and RPE (F(1.23,11.08) = 120.0, *p* < 0.001), However, there was no significant effect of menstrual cycle phase on HR (*F*(2,18) = 1.8, *p* = 0.197) or RPE (*F*(2,18) = 0.9, *p* = 0.427), and no significant phase × speed interaction was found for HR (*F*(3.49,31.40) = 1.6, *p* = 0.194) or RPE (*F*(2.68,24.12) = 0.1, *p* = 0.946).

TABLES 1 & 2. ABOUT HERE.

**Lactate (Threshold and OBLA)**

Running speeds at LT in the EF, LF, and ML phases were: 11.38 ± 0.55 km·h-1, 11.60 ± 0.86 km·h-1 and 11.60 ± 0.59 km·h-1 respectively. There was no significant effect of menstrual cycle phase on speed at LT (*F*(2,18) = 0.521, *p* = 0.602). Corresponding speeds at OBLA in each of those same phases were: 15.13 ± 1.40 km·h-1, 15.26 ± 1.74 km·h-1 and 14.87 ± 1.39 km·h-1 respectively. Similarly, there was no significant effect of menstrual cycle phase on speed at OBLA (*F*(2,18) = 0.702, *p* = 0.508).

**V̇O2max Test**

Results from the second part of the treadmill test can be seen in Table 3. There were no significant differences between menstrual cycle phases for V̇O2max (*F*(2,18) = 1.329, *p* = 0.290), TTE (*F*(2,18) = 0.687, *p* = 0.516), HRmax (*F*(2,16) = 0.294, *p* = 0.759) or Lapeak (*F*(2,18) = 0.217, *p* = 0.807).

TABLE 3. ABOUT HERE.

**DISCUSSION**

The aim of this study was to determine the effect of the menstrual cycle on RE in trained runners. The main finding was that, in the ML phase, V̇O2 is increased, signifying an impaired RE. Moreover, the absence of an interaction between menstrual cycle phase and running speed on RE indicates that the effect is independent of running speed. The results confirm previous findings of significantly increased V̇O2 at 70-80% V̇O2max in the ML phase compared with the EF phase.6,10 Whilst there is some evidence that the effect may dissipate at intensities lower than those of the present study,10 further research is required to confirm. Moreover, it is important to acknowledge that such intensities may be less economical17 and are unlikely to be encountered by athletes during training and competition.30

The observed increase in resting TC in the ML phase is in line with previous research,6-8,23 and likely due to the increase in progesterone16 which acts on the thermoregulation-associated preoptic/anterior regions of the hypothalamus.31 Although exercise TC was not measured in the present study, the increase in resting TC in the ML phase is reported to be sustained during exercise,8,15 indicating an elevated setpoint temperature15 and a corresponding increase in thermoregulatory, circulatory and metabolic strain6 which may impair RE.13,32,33 As a result, athletes may experience decreased performances during this phase of the menstrual cycle. Indeed, exercise performance has been shown to decrease in hot and/or humid conditions in the ML phase; although the same studies found no effect of elevated TC on performance in temperate conditions.7,34 The implications of the findings of the present study, therefore, may be relevant to athletes competing in extreme environmental conditions where the body is under increased physiological stress.

The present study is the first to observe an impaired RE in the ML phase compared to the EF and LF phases; possibly highlighting the implications of higher levels of progesterone that occur in this phase. Studies that have investigated the effects of the menstrual cycle on exercise economy have either failed to test in the LF phase,6 or only observed a significant difference in RE between the ML and EF phases.17 Concentrations of ovarian hormones often show high levels of inter- and intra-individual variation,3 which may explain the contrasting findings. In effect, longitudinal monitoring over several cycles may be required to identify, on an individual basis, the possible detrimental effects of hormonal fluctuations on exercise performance and training.35

The increase in V̇E between the ML phase and the LF phase in the present study supports previous research9,10,17,28 and is most likely due to increases in sympathetic drive and stimulation of chemoreceptors.17,36 Increased V̇E could impair exercise economy by increasing the oxygen cost of breathing.37 Indeed, when ventilation is mechanically assisted by means of a ventilator, V̇O2 has been shown to be reduced during incremental exercise with no corresponding changes in HR or TTE.37 Although TTE does not appear to be affected by an increase in V̇E during incremental exercise, there is evidence that an increased oxygen cost of breathing can impair TTE during fixed-intensity submaximal exercise.38,39 Then again, it is important to recognise that the effects of altered exercise V̇E may be influenced by training status9,37 and therefore have different performance implications for different populations.

Research into the effects of the menstrual cycle on elite and well-trained athletes has often found no effect of phase on performance despite menstrual cycle related changes in physiological variables, as above.5,7 However, it should be noted that TTE protocols as used in both this and other studies5,7,38 have been shown to be an unreliable measure of performance.39 Then again, worsened performance in the ML phase has been found in the Yo-Yo intermittent endurance test40 and in tests of maximal isometric force.41 It is also worth noting that qualitatively, both recreational and elite athletes feel that there are times in their menstrual cycle when performance is negatively affected42 and that this is particularly in the ML and late luteal phase due to premenstrual syndrome and premenstrual dysphoric disorder.43,44 In short, if endurance performance is affected by changes across the menstrual cycle it seems likely that the effect is quite subtle and, as such, may require a time-trial3 to give the best chance of detecting that effect.

Although resting HR has been shown to increase in the ML phase7,18 due to increased sympathetic activity,45 the results of the present study, and several others,5,7,10 found no effect of menstrual cycle phase on exercise HR or HRmax. Oestrogen is associated with increased nitric oxide bioavailability, promoting vasodilation, which results in a lowering of blood pressure and, possibly, HR.46 Therefore, high oestrogen levels in the ML phase may counteract the HR-elevating effect of progesterone.

Menstrual cycle phase did not affect RPE in the current study, which confirms some previous research,4,5,40 but contrasts with others.8,47 It is difficult to explain the lack of an effect of menstrual cycle phase on RPE given that oestrogen and progesterone are associated with alterations in pain, particularly in the late luteal and EF phases.48 Nevertheless, given that RPE is closely associated with HR in active individuals,47,49 the lack of a response of menstrual cycle phase on RPE in the current study is in-line with the absence of any corresponding effect on HR.

In line with the majority of the literature, there was no effect of menstrual cycle phase on body mass,5,40 La,5,6,10 or V̇O2max.4,43 The absence of changes in V̇O2max and body mass provide evidence that there was no increase or decrease in fitness or body composition that could have affected RE. Variables that can affect RE other than resting Tc and HR, such as footwear, environmental conditions, and running surface12 were controlled in this study. However, it should be noted that the technique of running on a treadmill is different to that of running outdoors, and requires altered muscle recruitment.31 Future studies should consider using portable oxygen analysers in a field-testing environment to confirm the effects of the menstrual cycle on RE in a more relevant setting for competitive athletes.12,31

1. **Conclusions**

The results of this study support previous reports of impaired RE in the ML phase of the menstrual cycle, when progesterone levels are high, which corresponded with increased resting TC and exercise V̇E. Whilst this impairment in RE did not affect TTE during a maximal treadmill test, the response should be particularly considered by female athletes racing during the ML phase, and by coaches when monitoring their female athletes during training. The study confirms previous research showing that exercise HR, La, and RPE are not affected by menstrual cycle phase. Further research is needed to examine the effects of menstrual cycle phase on exercise performance to establish any detrimental effects as a result of impaired RE, as well as investigating whether the effects of an impaired RE are exacerbated in extreme environmental conditions.

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**Author contributions**

EG and MG designed the study. EG carried out the data collection. EG and MG performed the statistical analyses. All authors contributed to the drafting of the manuscript, have read and approved the final version, and agree with the order and presentation of the authors.

**Competing interests**

The authors declare that they have no competing interests.

**References**

1. Dubey RK, Jackson EK. Estrogen-induced cardiorenal protection: Potential cellular, biochemical, and molecular mechanisms. *Am J Physiol Renal Physiol* 2001;**280**:F365-88.
2. Heritage AS, Stumpf WE, Sar M, Grant LD. Brainstem catecholamine neurons are target sites for sex steroid hormones. *Science* 1980;**207**:1377-9.
3. Oosthuyse T, Bosch AN. The effect of the menstrual cycle on exercise metabolism: Implications for exercise performance in eumenorrhoeic women. *Sports Med* 2010;**40**:207-27.
4. Janse de Jonge XAK. Effects of the menstrual cycle on exercise performance. *Sports Med* 2003;**33**:833-51.
5. De Souza MJ, Maguire MS, Rubin KR, Maresh CM. Effects of menstrual phase and amenorrhea on exercise performance in runners. *Med Sci Sports Exerc* 1990;**22**:575-80.
6. Hessemer V, Bruck K. Influence of menstrual cycle on thermoregulatory, metabolic, and heart rate responses to exercise at night. *J Appl Physiol* 1985;**59**:1911-7.
7. Janse de Jonge XA, Thompson MW, Chuter VH, Silk LN, Thom JM. Exercise performance over the menstrual cycle in temperate and hot, humid conditions. *Med Sci Sports Exerc* 2012;**44**:2190-8
8. Pivarnik JM, Marichal CJ, Spillman T, Morrow JR,Jr. Menstrual cycle phase affects temperature regulation during endurance exercise. *J Appl Physiol* 1992;**72**:543-8.
9. Schoene RB, Robertson HT, Pierson DJ, Peterson AP. Respiratory drives and exercise in menstrual cycles of athletic and nonathletic women. *J Appl Physiol Respir Environ Exerc Physiol* 1981;**50**:1300-5.
10. Smekal G, von Duvillard SP, Frigo P, Tegelhofer T, Pokan R, Hofmann P, *et al*. Menstrual cycle: No effect on exercise cardiorespiratory variables or blood lactate concentration. *Med Sci Sports Exerc* 2007;**39**:1098-1106.
11. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc* 1980;**12**:357-60.
12. Barnes KR, Kilding AE. Running economy: Measurement, norms, and determining factors. *Sports Med Open* 2015;**1**:8.
13. Thomas DQ, Fernhall BO, Granat H. Changes in running economy during a 5-km run in trained men and women runners. *J Strength Cond Res* 1999;**13**:162-7
14. Marshall J. Thermal changes in the normal menstrual cycle. *Br Med J* 1963;**1**:102-4.
15. Marsh SA, Jenkins DG. Physiological responses to the menstrual cycle: Implications for the development of heat illness in female athletes. *Sports Med* 2002;**32**:601-14.
16. Israel SL, Schneller O. The thermogenic property of progesterone. *Fertil Steril* 1950;**1***:*53-65*.*
17. Williams TJ, Krahenbhul GS. Menstrual cycle phase and running economy. *Med Sci Sports Exerc* 1997;**29**:1609-18.
18. Tenan MS, Brothers RM, Tweedell AJ, Hackney AC, Griffin L. Changes in resting heart rate variability across the menstrual cycle. *Psychophysiology* 2014;**51**:996-1004.
19. Fuller JT, Bellenger CR, Thewlis D, Tsiros MD, Buckley JD. The effect of footwear on running performance and running economy in distance runners. *Sports Med* 2015;**45**:411-22.
20. Reed BG, Carr BR. *The normal menstrual cycle and the control of ovulation.* 2018. In: Feingold KR, Anawalt B, Boyce A, *et al.* (Eds.), *Endotext [Internet].* Dartmouth (MA): MDTest.com, Inc; 2000; <https://www.ncbi,nlm.nih.gov/books/NBK279054/>
21. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci* 1996;**14**:321-7.
22. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982;**14**:377-81.
23. Hessemer V, Bruck K. Influence of menstrual cycle on shivering, skin blood flow, and sweating responses measured at night. *J Appl Physiol* 1985;**59**:1902-10.
24. Lenton EA, Landgren BM, Sexton L. Normal variation in the length of the luteal phase of the menstrual cycle: Identification of the short luteal phase. *Br J Obstet Gynaecol* 1984;**91**:685-9.
25. Schaumberg MA, Jenkins DG, Janse de Jonge XAK, Emmerton LM, Skinner TL. Three-step method for menstrual and oral contraceptive cycle verification. *J Sci Med Sport* 2017;**20**:965-9.
26. Rossiter HB, Ward SA, Kowalchuk JM, Howe FA, Griffiths JR, Whipp BJ. Dynamic asymmetry of phosphocreatine concentration and O2 uptake between the on- and off-transients of moderate- and high-intensity exercise in humans. *J Physiol* 2002;**541**:991-1002.
27. Newell J, Higgins D, Madden N, Cruickshank J, Einbeck J, McMillan, K, *et al*. Software for calculating blood lactate endurance markers. *J Sports Sci* 2007;**25**:1403-9.
28. Beaver WL, Wasserman K, Whipp BJ. Improved detection of lactate threshold during exercise using a log-log transformation. *J Appl Physiol* 1985;**59**:1936-40.
29. Maron MB, Horvath SM, Wilkerson JE, Gliner JA. Oxygen uptake measurements during competitive marathon running. *J Appl Physiol* 1976;**40**:836-8.
30. Kolka MA, Stephenson LA. Effect of luteal phase elevation in core temperature on forearm blood flow during exercise. *J Appl Physiol* 1997;**82**:1079-83.
31. Bailey SP, Pate RR. Feasibility of improving running economy. *Sports Med* 1991;**12**:228-36.
32. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *Sports Med* 2004;**34**:465-85.
33. Tenaglia SA, McLellan TM, Klentrou PP. Influence of menstrual cycle and oral contraceptives on tolerance to uncompensable heat stress. *Eur J Appl Physiol Occup Physiol* 1999;**80**:76-83.
34. Wactawski-Wende J, Schisterman EF, Hovey KM, Howards PP, Browne RW, Hediger M, *et al.* BioCycle study: design of the longitudinal study of the oxidative stress and hormone variation during the menstrual cycle. *Paediatr Perinat Epidemiol* 2009;**23**:171-84
35. Brar TK, Singh KD, Kumar A. (2015). Effect of different phases of menstrual cycle on heart rate variability (HRV). *J Clin Diagn Res* 2015;**9**:CC01-4.
36. Romer LM, Miller JD, Haverkamp HC, Pegelow DF, Dempsey JA. Inspiratory muscles do not limit maximal incremental exercise performance in healthy subjects. *Respir Physiol Neurobiol* 2007;**156**:353-61.
37. Romer LM, Lovering AT, Kaverkamp HC, Pegelow DF, Dempsey JA. Effect of inspiratory muscle work on peripheral fatigue of locomotor muscles in healthy humans. *J Physiol* 2006;**571(Pt 2)**:425-39.
38. Babcock MA, Pegelow DF, Harms CA, Dempsey JA. Effects of respiratory muscle unloading on exercise-induced diaphragm fatigue. *J Appl Physiol* 2002;**93**:201-6.
39. Bailey SP, Zacher CM, Mittleman KD. Effect of menstrual cycle phase on carbohydrate supplementation during prolonged exercise to fatigue. *J Appl Physiol* 2000;**88**:690-7.
40. Gosens W, Oomen JM, Kesselink MKC, Borghouts LB. Reliability of Time-Trial versus Time-to-Exhaustion Cycle Tests in healthy untrained subjects. *J Sci Cycling* 2015;**4**. doi:10.28985/jsc.v4i2.227.
41. Tenan MS, Hackney AC, Griffin L. Maximal force and tremor changes across the menstrual cycle. *Eur J Appl Physiol* 2016;**116**:153-60.
42. Bruinvels GB, Burden R, Brown N, Richards T, Pedlar C. The prevalence and impact of heavy menstrual bleeding (menorrhagia) in elite and non-elite athletes. *PLoS ONE* 2016;**11**:e0149881.
43. Constantini NW, Dubnov G, Lebrun CM. The menstrual cycle and sport performance. *Clin Sports Med* 2005;**24**:e51-82.
44. Takeda, Takashi, Imoto Y, Nagasawa H, Murova M, Shiina M. Premenstrual syndrome and premenstrual dysphoric disorder in Japanese collegiate athletes. *J Pediatr Adolesc Gynecol* 2015;**28**:215-18.
45. Jose AD, Stitt F, Collison D. The effects of exercise and changes in body temperature on the intrinsic heart rate in man. *Am Heart J* 1970;**79**:488-98.
46. Adkisson EJ, Casey DP, Beck DT, Gurovich AN, Martin JS, Braith RW. Central, peripheral and resistance arterial reactivity: Fluctuates during the phases of the menstrual cycle. *Exp Biol Med* 2010;**235**:111-8.
47. Julian R, Hecksteden A, Fullagar HH, Meyer T. The effects of menstrual cycle phase on physical performance in female soccer players. *PloS One* 2017;**12**:e0173951.
48. Hooper AE, Bryan AD, Eaton M. Menstrual cycle effects on perceived exertion and pain during exercise among sedentary women. *J Womens Health* 2011;**20**:439-46
49. Martin VT. Ovarian hormones and pain response: A review of clinical and basic science studies. *Gend Med* 2009;**6**:168-92.
50. Scherr J, Wolfarth B, Christie JW, Pressler A, Wagenpfeil S, Halle M. Associations between Borg’s rating of perceived exertion and physiological measures of exercise intensity. *Eur J Appl Physiol* 2013;**113**:147-55.

**Tables**

**Table 1.** The effects of menstrual cycle phase on heart rate during a sub-maximal treadmill test. Values are means ± standard deviation.

|  |  |  |  |
| --- | --- | --- | --- |
| Treadmill Speed  (km·h-1) | Heart Rate (b·min-1) | | |
| EF Phase | LF Phase | ML Phase |
| 9 | 129.3 ± 13.6 | 130.7 ± 14.3 | 134.4 ± 13.8 |
| 10 | 139.6 ± 12.8 | 139.3 ± 16.0 | 142.4 ± 13.2 |
| 11 | 147.1 ± 13.4 | 145.5 ± 15.0 | 148.2 ± 11.4 |
| 12 | 154.9 ± 13.2 | 153.9 ± 15.8 | 155.1 ± 10.2 |
| 13 | 165.0 ± 12.2 | 161.0 ± 13.8 | 163.9 ± 11.2 |
| 14 | 170.2 ± 11.3 | 167.6 ± 14.1 | 171.3 ± 9.5 |

Note: Note: EF = Early follicular; LF = Late follicular; ML = Mid-luteal.

**Table 2.** The effects of menstrual cycle phase on ratings of perceived exertion during a sub-maximal treadmill test. Values are means ± standard deviation.

|  |  |  |  |
| --- | --- | --- | --- |
| Treadmill Speed  (km·h-1) | Rating of Perceived Exertion | | |
| EF Phase | LF Phase | ML Phase |
| 9 | 8.5 ± 2.1 | 8.6 ± 1.9 | 9.0 ± 1.5 |
| 10 | 9.7 ± 1.7 | 9.9 ± 2.0 | 10.2 ± 1.2 |
| 11 | 11.0 ± 1.3 | 11.1 ± 1.9 | 11.5 ± 1.3 |
| 12 | 12.4 ± 1.0 | 12.5 ± 1.7 | 12.8 ± 1.4 |
| 13 | 13.5 ± 0.9 | 13.7 ± 1.7 | 14.0 ± 1.4 |
| 14 | 15.0 ± 0.9 | 15.2 ± 1.5 | 15.4 ± 1.6 |

Note: Note: EF = Early follicular; LF = Late follicular; ML = Mid-luteal.

**Table 3.** The effects of menstrual cycle phase on various physiological responses during an incremental treadmill test to exhaustion. Values are means ± standard deviation.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | V̇O2max  (mL·kg-1·min-1) | Time to Exhaustion  (mins) | HRmax  (b·min-1) | Lapeak  (mmol·L-1) |
| EF Phase | 58.15 ± 4.17 | 7.86 ± 1.17 | 180.67 ± 6.18 | 5.02 ± 1.32 |
| LF Phase | 58.37 ± 4.73 | 8.11 ± 1.15 | 179.22 ± 8.32 | 5.28 ± 1.37 |
| ML Phase | 59.70 ± 4.68 | 7.91 ± 1.28 | 180.33 ± 7.55 | 5.07 ± 1.13 |

**Note:** EF = Early follicular; HRmax = maximum heart rate; Lapeak = end-test blood lactate concentration; LF = Late follicular; ML = Mid-luteal; V̇O2max = maximal oxygen consumption.



\*†

**Figure 1.** The effects of menstrual cycle phase on oxygen uptake (V̇O2) during a submaximal treadmill test. Values are means; bars are standard deviations. Note: EF = Early follicular; LF = Late follicular; ML = Mid-luteal; \* Significant main effect of menstrual cycle phase; † significant main effect of treadmill speed.



\*†

**Figure 2.** The effects of menstrual cycle phase on minute ventilation during a submaximal treadmill test. Values are means; bars are standard deviations. Note: EF = Early follicular; LF = Late follicular; ML = Mid-luteal; \* Significant main effect of menstrual cycle phase; † significant main effect of treadmill speed.