

Effects of the Menstrual Cycle on Exercise Performance

Xanne A.K. Janse de Jonge

School of Exercise and Sport Science, Faculty of Health Sciences, The University of Sydney, Sydney, New South Wales, Australia

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Abstract

This article reviews the potential effects of the female steroid hormone fluctuations during the menstrual cycle on exercise performance. The measurement of estrogen and progesterone concentration to verify menstrual cycle phase is a major consideration in this review. However, even when hormone concentrations are measured, the combination of differences in timing of testing, the high inter- and intra-individual variability in estrogen and progesterone concentration, the pulsatile nature of their secretion and their interaction, may easily obscure possible effects of the menstrual cycle on exercise performance. When focusing on studies using hormone verification and electrical stimulation to ensure maximal neural activation, the current literature suggests that fluctuations in female reproductive hormones throughout the menstrual cycle do not affect muscle contractile characteristics. Most research also reports no changes over the menstrual cycle for the many determinants of maximal oxygen consumption ($\dot{V}O_{2\max}$), such as lactate response to exercise, bodyweight, plasma volume, haemoglobin concentration, heart rate and ventilation. Therefore, it is not surpris-

ing that the current literature indicates that $\dot{V}O_{2\max}$ is not affected by the menstrual cycle. These findings suggest that regularly menstruating female athletes, competing in strength-specific sports and intense anaerobic/aerobic sports, do not need to adjust for menstrual cycle phase to maximise performance.

For prolonged exercise performance, however, the menstrual cycle may have an effect. Even though most research suggests that oxygen consumption, heart rate and rating of perceived exertion responses to sub-maximal steady-state exercise are not affected by the menstrual cycle, several studies report a higher cardiovascular strain during moderate exercise in the mid-luteal phase. Nevertheless, time to exhaustion at sub-maximal exercise intensities shows no change over the menstrual cycle. The significance of this finding should be questioned due to the low reproducibility of the time to exhaustion test. During prolonged exercise in hot conditions, a decrease in exercise time to exhaustion is shown during the mid-luteal phase, when body temperature is elevated. Thus, the mid-luteal phase has a potential negative effect on prolonged exercise performance through elevated body temperature and potentially increased cardiovascular strain. Practical implications for female endurance athletes may be the adjustment of competition schedules to their menstrual cycle, especially in hot, humid conditions. The small scope of the current research and its methodological limitations warrant further investigation of the effect of the menstrual cycle on prolonged exercise performance.

Throughout ovulatory menstrual cycles, women are exposed to continuously changing female steroid hormone profiles. Estrogen starts to increase half-way through the follicular phase to reach a peak just prior to ovulation, while during the middle of the luteal phase both estrogen and progesterone are elevated. Research investigating large fluctuations in female steroid hormones (such as during pregnancy, menopause and hormone administration) has shown that both estrogen and progesterone cause many physiological effects, including changes in the thermoregulatory, respiratory and renal system. These secondary effects of estrogen and progesterone and their interaction may in turn influence exercise performance.

The research literature is often equivocal concerning the effects of the smaller menstrual cycle hormone fluctuations on exercise performance. Lebrun^[1] thoroughly reviewed the early literature on the effects of the different phases of the menstrual cycle on athletic performance and reported gaps and conflicts in the literature for many aspects of exercise performance. The present review will report on

the current status in the literature and will focus on three important aspects of exercise performance, i.e. muscle contractile characteristics, maximal oxygen consumption ($\dot{V}O_{2\max}$) and prolonged exercise performance. Firstly, the methodological considerations in menstrual cycle research will be determined to assist in the review of the literature to follow.

1. Methodological Considerations in Menstrual Cycle Research

1.1 Verification of Menstrual Cycle Phase

To be able to investigate the potential effects of menstrual cycle phase on exercise performance, it is of vital importance to accurately verify the menstrual cycle phase at the time of testing. Most verification methods concentrate on the occurrence of ovulation to enable division of the menstrual cycle into follicular and luteal phases. This verification not only ensures that the correct/intended phase is investigated, it also avoids inclusion of non-ovulatory and luteal phase deficient (LPD) cycles. Both anovulation and LPD are characterised by low progesterone

concentrations during the second half of the cycle. De Souza et al.^[2] showed a high frequency of LPD (43%) and anovulation (12%) in recreational runners and a high level of inconsistency from one menstrual cycle to the next. These changes in menstrual cycle function are not necessarily reflected in alterations in bleeding pattern.^[3] Ovulatory disturbances therefore often remain unperceived by apparently regularly menstruating women, resulting in uncertainty about the prevalence of anovulation and LPD in the general population. Thus, especially in active women, even when regular bleeding occurs, one cannot assume a consistent menstrual cycle with regular hormone concentrations. To avoid inclusion of non-ovulatory/LPD menstrual cycles and to be able to draw valid conclusions about the effects of menstrual cycle phase on measured variables, it is necessary to accurately verify menstrual cycle phase.

Early studies investigating the menstrual cycle often relied on counting the days from the onset of menses. It was assumed that study participants had regular ovulatory menstrual cycles and followed 'normal' hormone fluctuations throughout the menstrual cycle. One problem with this method is that, in general, the follicular phase is more variable in length than the luteal phase. Thus, unless days are counted backwards, in retrospect, it is difficult to predict the day of ovulation. The main problem is the assumption that all women who menstruate regularly also ovulate regularly. As mentioned, there is a high incidence of anovulation and LPD in active women with regular bleeding.^[2] Thus, counting days from onset of menses does not differentiate ovulatory from anovulatory cycles and will therefore give misleading information about menstrual cycle phase.

A second well established method for menstrual cycle phase determination is basal body temperature (BBT) charting. Most ovulatory women have an increase in BBT of approximately 0.3°C after ovulation, which is sustained throughout the luteal phase.^[4,5] BBT charting is a useful method for identifying the approximate day of ovulation, and thus the relative length of follicular and luteal phases.

This method, however, does not give information about actual hormone levels. Moreover, the relationship between BBT and ovulation may vary considerably, with some women not showing an increase in BBT during the luteal phase.^[6] Although it is tempting to assume that an increase in BBT reflects an increase in progesterone, a poor correlation between BBT and progesterone concentration has been found.^[6-8] Thus although BBT charting may give an indication of whether or not ovulation has occurred, its reliability and its reflection of progesterone level should be treated with caution.

Urinary luteinising hormone (LH) concentration can be determined using ovulation predictor kits, consisting of colorimetric enzyme immunoassays of urinary LH. The time from peak serum LH concentration to the urinary LH peak was shown to be 2 ± 2 hours (mean \pm standard error), indicating that urinary LH reflects serum levels relatively quickly.^[9] Once the LH surge has been shown to occur, it can be assumed with a confidence level of 95% that ovulation will take place within the next 14–26 hours.^[9]

The fourth method for menstrual cycle phase verification is the measurement of estrogen and progesterone. The hormone concentrations can be measured in serum and saliva or their metabolites can be measured in urine. The measurement of estrogen and progesterone in saliva is non-invasive and convenient. The steroid concentrations in saliva reflect the free portion of the serum concentration and are much lower than in serum (0.2% for estrogen^[10] and 1.3% for progesterone^[11]). The main problem, therefore, is that methods with much greater sensitivity need to be developed to enable accurate measurements. The measurement of estrogen and progesterone metabolite concentrations in urine can also give an indication of menstrual cycle phase.^[12] A problem with this method is the impracticality of 24-hour urine collections. If early morning urine is analysed instead, the adjustment to standardised 24-hour collection may cause additional error in the measurements. Based on the greater potential for inaccuracy in salivary and urinary measures, it is not surprising that most recent studies verify menstrual cycle phase

Table I. Menstrual cycle phase terminology with corresponding days of the menstrual cycle, where possible accompanied by an indication of corresponding hormone concentrations of oestrogen and progesterone

Terminology with corresponding hormone concentrations			Terminology including a range of hormone concentrations
menstrual cycle phase (days of menstrual cycle ^a)	estrogen concentration	progesterone concentration	menstrual cycle phase (days of menstrual cycle ^a)
Early-follicular (2–7)	Low	Low	Follicular (1–13) Pre-ovulatory (1–13) Mid-follicular (6–9) ^[15]
Late-follicular (9–13)	High	Low	Mid-cycle (12–18) ^[16] Ovulatory (3–5 days around ovulation) ^[17]
Mid-luteal (18–24)	High	High	Ovulation (14) Luteal (15–28) Post-ovulatory (15–28)

a Based on a 28-day cycle with ovulation occurring on day 14.

with the well-established method of serum estrogen and progesterone concentration measurements.

The verification of menstrual cycle phase is based on an increase in progesterone from the follicular to the luteal phase to indicate that ovulation has occurred. However, the minimum post-ovulatory progesterone concentration required to confidently verify ovulation appears undecided. Israel et al.^[13] suggested a minimum of 9.54 nmol/L, while Landgren et al.^[14] set the limit at 16 nmol/L. For research purposes, the higher, more conservative progesterone limit of 16 nmol/L increases the chance of detecting changes over the menstrual cycle that are related to hormone fluctuations. Estrogen concentration measurements are important in identifying the late-follicular estrogen peak. Measurement of both estrogen and progesterone is the only method that can identify between the three distinct phases: (i) early-follicular phase (low estrogen and progesterone); (ii) late-follicular phase (high estrogen and low progesterone); and (iii) mid-luteal phase (high estrogen and progesterone) [see table I]. As this article reviews the effects of the female steroid hormone fluctuations throughout the menstrual cycle on exercise performance, the main focus will be on those studies that measured estrogen and progesterone to verify menstrual cycle phase.

1.2 Timing of Testing

A further consideration in research on the influence of the menstrual cycle on exercise performance

is the timing of the testing with respect to the menstrual cycle. A potential effect of the hormone fluctuations during the menstrual cycle on exercise performance is most likely to be found when testing is conducted during those phases of the menstrual cycle with significantly different hormone levels. During the early-follicular phase, both estrogen and progesterone concentrations are low. Estrogen starts to increase halfway through the follicular phase to reach a peak in the late-follicular phase and then sharply drops just prior to ovulation. After ovulation, both estrogen and progesterone increase until a plateau is reached during the mid-luteal phase. In the late luteal phase, estrogen and progesterone decrease again.^[18] Based on this pattern of estrogen and progesterone throughout the menstrual cycle, three distinct phases can be identified (see section 1.1 and table I). As also shown in table I, the terminology used for the different phases of the menstrual cycle often varies between studies. If, for example, the term 'follicular phase' is used, it remains unclear if this term refers to the early-follicular phase with its low estrogen and progesterone concentrations, the mid-follicular phase with potentially rising estrogen levels, or perhaps to the late-follicular phase with high estrogen and low progesterone concentrations. When reviewing results of different investigations, it is therefore important to determine the exact days of testing (and if possible the hormone levels on those days) to ensure that the same menstrual cycle phases are being compared. In this review, the menstrual cycle phases will be de-

defined as clearly as possible using the terms 'early-', 'mid-' and 'late-follicular' phase and 'mid-luteal' phase. Whenever the general terms 'follicular' and 'luteal' phase are used, these terms either refer to the whole menstrual cycle phase or indicate that the reviewed study did not provide detailed information about the timing of testing.

A further problem in menstrual cycle research is that different studies often investigate different phases of the menstrual cycle. Some may have compared the early-follicular phase with the few days prior to ovulation,^[19] while others compared the early-follicular phase,^[20] or the mid-follicular phase^[15] with the mid-luteal phase. Other studies conducted testing every week, then retrospectively fitted menstrual cycle phase to the test days.^[16] These different approaches to the timing of testing often arise from problems in the prediction of the exact phase of the menstrual cycle and the concurrent reproductive hormone concentrations. As the follicular phase is more variable in length than the luteal phase, it is difficult to predict the day of ovulation. A further problem is that the length of the menstrual cycle may vary from cycle to cycle, which may cause error when information from the previous cycle is used to predict the days of testing.

1.3 Pulsatile Secretion of Estrogen and Progesterone

In menstrual cycle research, large variations in hormone concentration between different phases of the menstrual cycle are expected. In the same menstrual cycle phase, there is also a large variability in hormone concentrations between women.^[21] In addition, it has been shown that within the same woman, progesterone levels fluctuate widely during the mid-luteal phase, with concentration changes of greater than 64 nmol/L within several hours.^[22] This large variation in hormone levels within each phase is partly due to the pulsatile secretion of these hormones (ultradian rhythm). In a study of diurnal variation in hormone secretion, it was shown that progesterone concentrations are highest in the morning,^[23] so that the time of day of testing should also be taken into account when comparing studies.

Another factor to consider is that exercise is known to increase both estrogen and progesterone concentrations.^[24,25] Therefore, hormone verification measurements should take place at rest.^[26] Even when hormone concentrations are measured under resting conditions, at a set time of day, it should be noted that rapid fluctuations in the reproductive and pituitary hormones may occur at any time. Therefore, the pre-test hormone concentration may not necessarily reflect hormone concentrations during testing.

1.4 Interaction of Estrogen and Progesterone

Another difficulty in interpreting menstrual cycle research stems from the interaction between estrogen and progesterone. Two women may have the same estrogen concentration at a certain point in the menstrual cycle, but may have very different progesterone levels.^[21] Thus, the effect of the same estrogen concentration may be different in the two women because of the interaction with progesterone. To emphasise the importance of interactive effects, some studies not only report estrogen and progesterone concentrations, but also the estrogen/progesterone ratio.^[21] This ratio may provide information about opposing effects of estrogen and progesterone. In addition, the product of estrogen and progesterone may reveal synergistic effects of estrogen and progesterone. This interaction between estrogen and progesterone needs to be considered in menstrual cycle research, especially during the mid-luteal phase, when large concentrations of both hormones are present.

2. Skeletal Muscle Contractile Characteristics During the Menstrual Cycle

Research investigating the muscle contractile characteristic strength throughout the menstrual cycle shows conflicting results. Sarwar et al.^[16] found that regularly menstruating women were stronger mid-cycle (defined as day 12–18 of the menstrual cycle). Phillips et al.^[27] reported an increase in adductor pollicis strength during the follicular phase, followed by a rapid decrease in strength

around ovulation. These two studies suggested that estrogen may have a strengthening effect on skeletal muscle. However, Bassey et al.^[28] found a negative association between estrogen concentration and handgrip strength. In contrast, Greeves et al.^[29] reported the greatest strength during the mid-luteal phase and suggested that progesterone may be implicated in the regulation of strength production. Several other studies have found no change in the muscle contractile characteristic strength over the menstrual cycle.^[30-35]

These conflicting findings can largely be explained by methodological shortcomings. The main problem in the measurement of maximal muscle strength is ensuring that the contraction truly reflects the maximum force-generating capacity of the muscle. Even well-motivated individuals cannot always reach full neural activation of their muscles.^[36] The extent of neural activation can be determined by applying a superimposed electrical stimulus to the muscle during the performance of a maximal voluntary isometric contraction. When comparing strength over a period of time, such as in menstrual cycle research, it is especially important to ensure maximal neural activation using electrical stimulation during each test.

Of the aforementioned studies, only four used superimposed electrical stimulation to ensure full neural activation of the muscle.^[16,29,34,35] Two of these studies reported changes in muscle strength over the menstrual cycle. Sarwar et al.^[16] found an increase in strength at mid-cycle, while Greeves et al.^[29] reported the highest strength during the mid-luteal phase. However, White and Weekes^[34] and Janse de Jonge et al.^[35] reported no change in muscle strength over the menstrual cycle.

Sarwar et al.^[16] used superimposed electrical stimulation to test the skeletal muscle contractile characteristics strength, relaxation rate and fatigability of the quadriceps in ten young women during the menstrual cycle. These authors found that regularly menstruating women were stronger, more fatigable and had a longer relaxation time at mid-cycle. The major limitation of the study by Sarwar et al.^[16] is that hormone concentrations were not measured to

verify menstrual cycle phase. Therefore, this study may have included non-ovulatory/LPD menstrual cycles. Furthermore, mid-cycle was defined as day 12–18 of the menstrual cycle and for most women ovulation would occur during this period. Thus the female reproductive hormone concentrations would be expected to fluctuate significantly during this phase. The results of this study should be regarded with these limitations in mind.

Greeves et al.^[29] measured maximal isometric strength of the quadriceps with superimposed electrical stimulation in nine young women. Measurements were conducted at seven time points throughout the menstrual cycle, based on LH peak, and estrogen and progesterone concentrations were measured on five occasions. Greeves et al.^[29] found the lowest strength during the late-follicular phase (with rising estrogen levels) and the highest strength during the mid-luteal phase (with high progesterone levels). These authors speculated that progesterone may be involved in the regulation of strength, which was supported by the positive relationship found between relative force and progesterone ($r = 0.330$). The r^2 value of this relationship indicates that only 11% of the variability in strength could be explained by change in progesterone. The actual results for estrogen and progesterone, however, were not reported. Furthermore, Greeves et al.^[29] did not indicate a progesterone limit for verification of ovulation.

White and Weekes^[34] tested muscle contractile characteristics of the triceps surae with electrical stimulation at four time points during the menstrual cycle in six regularly menstruating women. These authors measured maximal voluntary isometric strength, maximally electrically evoked twitch and tetanus force and fatigability. The phases of the menstrual cycle were estimated retrospectively, by counting days backwards from the onset of the second menses. White and Weekes^[34] found no link between menstrual cycle phase and voluntary and electrically evoked contractile characteristics (strength and fatigability) of the triceps surae. Again, the major shortcoming was that White and Weekes^[34] did not measure hormone concentrations

to verify menstrual cycle phase. The study could therefore have included non-ovulatory/LPD menstrual cycles and, with only six study participants, this may have easily obscured possible effects of menstrual cycle phase on muscle contractile characteristics.

Janse de Jonge et al.^[35] investigated skeletal muscle contractile characteristics using electrical stimulation in 15 women. Testing was conducted in a way that ensured that the three distinct hormonal profiles of the menstrual cycle were represented (i.e. low estrogen and progesterone concentrations during the early-follicular phase, high estrogen and low progesterone during the late-follicular phase, and high estrogen and progesterone during the mid-luteal phase). A strict progesterone limit of 16 nmol/L was set for confirmation of ovulation and progesterone was significantly elevated during the mid-luteal phase. In addition, estrogen concentrations were significantly different for the three phases of the menstrual cycle. Janse de Jonge et al.^[35] reported no changes over the menstrual cycle for strength and fatigability of the quadriceps. Furthermore, no correlations were found between the measured muscle contractile characteristics and the hormone concentrations of estrogen and progesterone.^[35]

Isokinetic strength over the menstrual cycle has been investigated by several studies using hormone concentration measurements to verify menstrual cycle phase.^[32,33,35] No changes over the menstrual cycle were found for isokinetic knee flexion and extension.^[32,33,35] Two of these studies also showed no significant difference in fatigability over the menstrual cycle.^[33,35]

In summary, the current literature suggests that the fluctuations in female steroid hormones throughout the menstrual cycle do not affect muscle strength and fatigability. A practical implication of these findings would be that regularly menstruating female athletes in strength-specific sports do not need menstrual cycle adjustment to maximise their competitive ability.

3. Maximal Oxygen Consumption During the Menstrual Cycle

Several determinants of $\dot{V}O_{2\max}$ may be affected by the estrogen and progesterone fluctuations during the menstrual cycle. The three main physiological factors involved in $\dot{V}O_{2\max}$ are fuel availability, circulation and respiration. Fuel availability is determined by food intake, fuel storage and fuel mobilisation, which may in turn affect the blood lactate concentration in response to exercise. As $\dot{V}O_{2\max}$ is often expressed per kilogram of bodyweight (ml/kg/min), changes in bodyweight as a result of potential changes in fluid regulation may also affect $\dot{V}O_{2\max}$. Furthermore, fluid regulation may influence plasma volume and haemoglobin concentration, which would affect the oxygen carrying capacity of blood. Possible changes in plasma volume may have an effect on heart rate, which is an important determinant of cardiac output. Finally, ventilation is needed to supply oxygen to the lungs. The potential effects of the menstrual cycle on these determinants of $\dot{V}O_{2\max}$ will be reviewed to assist in determining the effect of the menstrual cycle on $\dot{V}O_{2\max}$.

3.1 Metabolism and Blood Lactate Concentration in Response to Exercise

Several studies reported changes in exercise substrate metabolism over the menstrual cycle,^[37-39] suggesting an enhanced lipid metabolism during the mid-luteal phase. Other investigations found no difference in substrate metabolism between the phases of the menstrual cycle.^[40,41] Bonen et al.^[42] found a change in exercise substrate metabolism over the menstrual cycle in glucose-loaded women, while substrate responses in fasted and control women were similar. These results suggest that metabolism is likely to be affected by an interaction between menstrual cycle phase and nutritional status. For more detailed information on metabolism during the menstrual cycle, the reader is referred to the review by Ashley et al.^[43]

When reviewing the literature on lactate response to exercise over the menstrual cycle, inconsistencies were also found. Some studies reported a higher

blood lactate concentration in response to exercise during the mid-follicular phase.^[15,44,45] They speculated that estrogen enhanced lipid oxidation^[15] and spared glycogen,^[44] thus causing a lower lactate response to exercise in the mid-luteal phase of the menstrual cycle. Many other studies, however, found no significant changes over the menstrual cycle in lactate response to exercise.^[38,40-42,46-48]

The lactate response to exercise is likely to be influenced by substrate metabolism, which, in turn, is affected by nutritional status. The decrease in lactate response to exercise during the mid-luteal phase found by Jurkowski et al.^[44] and McCracken et al.^[15] may have been due to differences in nutritional status. Furthermore, the mean progesterone level in the study by Jurkowski et al.^[44] during the mid-luteal phase was lower than in most other studies (28.3 ± 7 nmol/L versus >40 nmol/L). Their results should therefore be regarded with some caution due to potential inclusion of non-ovulating/LPD women in this study. This may have also been the case for Lavoie et al.,^[45] who found a decreased lactate response to exercise during the mid-luteal phase. Lavoie et al.^[45] reported low mid-luteal phase progesterone concentrations in two of their seven study participants and it remains unclear whether or not these non-ovulating/LPD participants were included in the analysis.

Of all previously mentioned lactate studies, only two exerted strict dietary control (for 2–3 days before testing) and verified menstrual cycle phase. These two studies found no changes in lactate response to exercise over the menstrual cycle.^[40,42] Over all, it seems most likely that the menstrual cycle does not affect blood lactate concentration in response to exercise.

When reviewing the effects of menstrual cycle changes in lactate response to exercise on exercise performance, Jurkowski et al.^[44] reported an improvement in exercise time to exhaustion at 90% of $\dot{V}O_{2\max}$ during the mid-luteal phase. As mentioned earlier, possible inclusion of non-ovulating/LPD study participants and possible differences in nutritional status should be considered for this study. Furthermore, Jurkowski et al.^[44] showed no change

over the menstrual cycle for maximum power output, measured during an incremental exercise test to exhaustion. De Souza et al.^[41] also found no significant changes over the menstrual cycle in $\dot{V}O_{2\max}$ and time to exhaustion. Thus, even in the unlikely event that a certain combination of nutritional status and menstrual cycle phase were to cause a change in lactate response to exercise, this seems unlikely to have an effect on $\dot{V}O_{2\max}$.

3.2 Bodyweight

Many women report changes in bodyweight and a bloated feeling throughout the menstrual cycle, indicating potential changes in the distribution of body fluids. Most studies have found no significant change in bodyweight over the menstrual cycle.^[5,32,41,49] These studies, however, conducted testing on only two or three occasions throughout the menstrual cycle. In a study with daily bodyweight measurements, in 28 young women, the highest bodyweight was found in the late luteal phase and the first days of menstruation.^[50] This was immediately followed by an abrupt weight loss. A short peak in bodyweight just after ovulation was also found.^[50] The time of ovulation in this study, however, was estimated from BBT patterns and was not verified with hormone measurements. Also, for bodyweight loss during exercise, most studies have reported no changes over the menstrual cycle.^[17,20,51,52] These findings may indicate that estrogen and progesterone changes during the menstrual cycle do not affect fluid regulation. An alternative explanation may be that the menstrual cycle affects the distribution of fluid within the body, rather than absolute fluid retention or excretion.

3.3 Plasma Volume, Haematocrit and Haemoglobin Concentration

Information about a possible change in fluid distribution may be detected by investigating changes in plasma volume, haematocrit and haemoglobin concentration over the menstrual cycle. Fortney et al.^[53] measured the absolute plasma volume and red cell mass of five women and found no difference between the follicular and luteal phase. These au-

thors then investigated daily resting plasma volume changes in eight women, calculated from haematocrit and haemoglobin change and the known absolute plasma volume. A peak in plasma volume was found within 2 days of the estimated day of ovulation, followed by a dip during the early luteal phase and an increase during the mid- to late-luteal phase of the menstrual cycle.^[53] Stephenson and Kolka,^[54] however, reported a lower resting plasma volume during the mid-luteal phase (day 19–22) than the early-follicular phase. Support for the plasma volume pattern reported by Fortney et al.^[53] was found in a large study by Vellar^[55] ($n = 477$; 1270 blood samples). This study showed that the highest haematocrit and haemoglobin concentration was found around day 18 of the menstrual cycle (mean of values from day 15–19), which coincides with the lowest plasma volume in the study by Fortney et al.^[53] None of these three studies verified menstrual cycle phase with hormone measurements and their results should be interpreted with this limitation in mind. The fact that the studies by both Fortney et al.^[53] and Vellar^[55] reported the same pattern over the menstrual cycle warrants further investigation of fluid regulation and haematology at multiple time points during the menstrual cycle.

Several studies with hormone verification have found no change in haematocrit and haemoglobin concentration over the menstrual cycle.^[32,56-58] Dombovy et al.^[38] reported a lower haemoglobin concentration during the mid-luteal phase. In contrast, Jurkowski et al.^[44] found a higher resting haemoglobin during the mid-luteal phase. As mentioned previously, this result may be questionable due to possible inclusion of non-ovulatory/LPD cycles in this study. Stachenfeld et al.^[20] reported a higher resting haematocrit during the mid-luteal phase. Observing the limitation that all these studies conducted testing at only two time points throughout the menstrual cycle, most evidence suggests that resting haemoglobin and haematocrit are not affected by the menstrual cycle.

An additional factor to consider when investigating haemoglobin concentration over the menstrual cycle is the actual blood loss during menstruation. In

a large population study on menstrual blood loss, it was shown that the 80% range for blood loss was 10–90mL.^[59] This study reported a mean blood loss of 43mL in 476 women aged between 15 and 50 years. However, 11% of the women lost more than 80mL of blood during menstruation. For these women, a significantly lower haemoglobin concentration was found than for the women who lost 1–60mL.^[59] Thus, the actual blood loss during menstruation may result in a decrease in haemoglobin concentration at that time for some women.

When reviewing the effects of the menstrual cycle on plasma volume changes during exercise, as calculated from haematocrit and haemoglobin changes, conflicting findings are evident. Stephenson and Kolka^[54] reported a larger fluid shift out of the vasculature during the early-follicular phase, decreasing plasma volume at a faster rate than during the mid-luteal phase. The major limitation of this study was that the menstrual cycle phase of the five participants in this study was not verified by hormone measurements. Gaebelein and Senay^[57] also found a faster decrease in plasma volume during exercise during the early-follicular phase. Although Gaebelein and Senay^[57] measured hormone levels for the five study participants, the reported mean progesterone concentration in the mid-luteal phase was very low (14.6 nmol/L). Therefore, the possibility of inclusion of non-ovulatory/LPD cycles should be considered. Other studies with larger participant numbers and menstrual cycle phase verification through hormone measurements, found no change in plasma volume shifts between the phases of the menstrual cycle during exercise.^[15,41] Based on the number of study participants and proper menstrual cycle verification in these latter studies, plasma volume changes during exercise are likely to be unaffected by the menstrual cycle.

In summary, a study with daily measurements reported a changing pattern in plasma volume over the menstrual cycle, which was supported by another study with multiple measurements and a large number of study participants. A major limitation was that both these studies did not verify menstrual cycle phase with hormone measurements. Most

studies with hormone verification showed no change over the menstrual cycle in haematocrit, haemoglobin concentration and plasma volume changes during exercise. These studies, however, only conducted testing at two time points (early- or mid-follicular versus mid-luteal phase). During menstruation, haemoglobin concentration may be decreased by the actual blood loss. These findings warrant further investigation of fluid regulation and haematology at multiple time points during the menstrual cycle.

3.4 Heart Rate

Plasma volume expansion is associated with increased stroke volume and decreased heart rate^[60] due to changes in blood viscosity and central venous pressure. Thus, changes in plasma volume over the menstrual cycle, as suggested in the previous section,^[53,54] may alter heart rate throughout the menstrual cycle. Several studies have found an increased heart rate during the mid-luteal phase.^[48,51,61-63] Moran et al.,^[63] who measured resting heart rate, suggested that an estrogen induced change in blood volume may account for the heart rate fluctuation over the menstrual cycle.

An alternative explanation for this mid-luteal phase increase in heart rate may be based on the increased body temperature at that time. Increased heart rate has been shown to occur with increased body temperature,^[64-66] at a rate of 7 beats/min for each 1°C rise in core temperature.^[67] During exercise, there is a competition between blood flow to the exercising muscle (to support metabolism) and skin blood flow (to dissipate heat). The increased skin blood flow may result in a decrease in central venous pressure accompanied by an increase in heart rate to maintain cardiac output.^[66] In addition, approximately 40% of the increase in heart rate with increased body temperature was suggested to be related to a direct effect of temperature on the sinoatrial node.^[64] The potential increase in heart rate during the luteal phase based on an increase in BBT of 0.3–0.5°C would be small (approximately 3 beats/min). It is therefore not surprising that most

studies reported no change in resting and/or exercise heart rate over the menstrual cycle.^[32,38,41,44,52,68-70]

3.5 Ventilation

Animal research has suggested that progesterone may increase ventilation (\dot{V}_E) through a central effect in the hypothalamus and that this respiratory response to progesterone is modulated by estrogen.^[71] In addition, \dot{V}_E has been shown to be affected by body temperature.^[72-74] Thus, during the luteal phase of the menstrual cycle, when both progesterone and core temperature are elevated, an increase in \dot{V}_E may be expected. Conflicting results regarding \dot{V}_E and arterial carbon dioxide tension (pCO_2) over the menstrual cycle were found in the literature. Preston et al.^[70] reported a lower resting arterial pCO_2 during the luteal phase of the menstrual cycle, while Dombovy et al.^[38] found this same result during exercise. Other studies showed increases in \dot{V}_E during the mid-luteal phase both at rest^[62,69] and during exercise.^[44,75] However, with exercise at intensities of 70% of $\dot{V}O_{2max}$ and higher, several studies reported no significant changes over the menstrual cycle in exercise \dot{V}_E .^[32,41,46,68,69] Since the increase in \dot{V}_E due to exercise is far greater than any possible increase caused by progesterone, exercise may have masked the progesterone effect on \dot{V}_E in this situation.

In healthy people, changes in \dot{V}_E are not expected to limit $\dot{V}O_{2max}$.^[76] This is confirmed for the menstrual cycle by Jurkowski et al.,^[44] who found a higher maximum \dot{V}_E for the mid-luteal phase and no change in maximum power output. Schoene et al.^[62] reported an increased ventilatory equivalent for oxygen (\dot{V}_E /oxygen consumption [$\dot{V}O_2$]) during the mid-luteal phase. This was accompanied by a decrease in exercise time to exhaustion in non-athletes, but no difference in $\dot{V}O_{2max}$ was shown.^[62] The remaining \dot{V}_E studies either found no change in \dot{V}_E over the menstrual cycle,^[38,41,46,69] or did not measure $\dot{V}O_{2max}$ over the menstrual cycle.^[70,75] Thus, $\dot{V}O_{2max}$, measured during incremental exercise, seems to be unaffected by possible changes in \dot{V}_E over the menstrual cycle.

3.6 Maximal Oxygen Consumption

As $\dot{V}O_{2\max}$ is the main physiological indicator of aerobic exercise performance, a potential change in $\dot{V}O_{2\max}$ over the menstrual cycle will have large practical implications for female athletes. When reviewing the determinants of $\dot{V}O_{2\max}$, most studies suggest that lactate response to exercise, body-weight, haemoglobin concentration and heart rate are not affected by the menstrual cycle. Although \dot{V}_E may be increased during the mid-luteal phase, it is unlikely that this will affect $\dot{V}O_{2\max}$ over the menstrual cycle. Thus, it is speculated that the menstrual cycle will not affect $\dot{V}O_{2\max}$.

This speculation is confirmed by the fact that most studies have found no change in $\dot{V}O_{2\max}$ over the menstrual cycle.^[38,41,44,46,69] However, the number of study participants in these studies was relatively low (between five and nine individuals). Furthermore, in the studies by Jurkowski et al.^[44] and Bembem et al.^[46] a low mean progesterone level was reported during mid-luteal phase (28 and 21 nmol/L, respectively) and the possible inclusion of non-ovulatory/LPD menstrual cycles cannot be disregarded. In a thorough investigation of 16 women, Lebrun et al.^[32] found a lower absolute $\dot{V}O_{2\max}$ during the mid-luteal phase than during the early-follicular phase. However, when expressed as relative $\dot{V}O_{2\max}$, this difference was no longer significant ($p = 0.06$).

In summary, most research suggests that the menstrual cycle does not affect $\dot{V}O_{2\max}$. These findings indicate that, based on $\dot{V}O_{2\max}$, there is no need for menstrual cycle adjustment for regularly menstruating female athletes competing in intense anaerobic/aerobic sports.

4. Prolonged Exercise Performance During the Menstrual Cycle

It is well established that BBT is increased during the luteal phase in most eumenorrheic women. This elevated temperature, combined with possible changes in fluid regulation, haematology and \dot{V}_E , may affect prolonged exercise performance, particularly in a hot environment.

4.1 Temperature Regulation

For over a century it has been known that BBT changes rhythmically throughout the menstrual cycle in eumenorrheic women.^[4,77-80] BBT increases approximately 0.3–0.5°C after ovulation and remains elevated throughout the luteal phase of the menstrual cycle.^[4,5,81] At the onset of menstruation, BBT decreases to its previous level and remains at this temperature throughout the follicular phase. Just prior to the following luteal phase elevation in BBT, a characteristic short temperature dip in the late-follicular phase is often, but not consistently, reported.^[4,79,80] Davis and Fugo^[79] showed this dip in less than 50% of 100 BBT graphs, while Marshall^[4] detected it in only 10% of the 1134 menstrual cycles recorded in their study.

The elevated BBT during the luteal phase has long been associated with the increased progesterone concentration during this phase.^[17,61,80,82] This association was based on the early progesterone administration^[82-84] and pregnancy studies,^[85] which clearly demonstrated an increased BBT concomitant with increased progesterone. The most widely accepted explanation for the elevated BBT during the luteal phase is that the thermoregulatory setpoint is increased.^[17,61,86,87] This would imply that the thresholds for all thermoregulatory effector responses are shifted in a similar direction during the luteal phase of the menstrual cycle. Furthermore, the increased luteal phase resting body temperature would remain elevated throughout exercise and/or heat stress.

The exact mechanism behind this increased thermoregulatory setpoint is not well understood. In animal research, progesterone administration has been shown to decrease the activity of warm sensitive neurons and increase the activity of cold sensitive neurons in the preoptic area.^[88] Furthermore, it was suggested that progesterone implantation in the preoptic area of rats increased colonic temperature.^[89] These findings indicate a central effect of progesterone in the preoptic area, resulting in an increased setpoint temperature. In contrast, a decrease in BBT has been reported in association with estrogen administration.^[81-85] Animal research has

shown that estrogen increased the activity of warm sensitive neurons in the pre-optic area.^[90] A central effect of estrogen, through direct action on preoptic neurons, has been suggested to decrease body temperature.^[90] Therefore, several studies have speculated that the potentially increased thermoregulatory setpoint during the luteal phase is related to the ratio between estrogen and progesterone.^[7,91,92]

Changes in thermoregulatory setpoint and effector responses over the menstrual cycle may be investigated by imposing exercise and/or heat stress. Some studies have not found a difference in resting body temperature between menstrual cycle phases at the onset of their stress testing.^[93-96] Others have reported that the difference in resting body temperature between the phases of the menstrual cycle disappeared during exercise and/or heat stress.^[5,97] However, these studies had low numbers of study participants^[5,93,94,97] and, except for Horvath and Drinkwater,^[5] did not verify menstrual cycle phase with progesterone measurements. More recent studies with hormonal verification of the menstrual cycle phase have shown that the increased resting body temperature during the mid-luteal phase remained elevated throughout exercise and/or heat stress.^[17,48,49,51,52,61,98] Several of these studies also reported an increased core temperature threshold for thermoregulatory effector responses during the mid-luteal phase.^[48,49,61,98] The findings of these studies and of many others without hormone verification^[99-103] support the increased thermoregulatory setpoint theory.

The question as to whether the shift in thermoregulatory setpoint is accompanied by a change in thermosensitivity for sweating and skin blood flow remains a topic of discussion in the current literature. Hessemer and Bruck^[61] reported an increased setpoint and a greater thermosensitivity (steeper slope of effector versus temperature graph) for sweating and cutaneous vasodilation in the mid-luteal phase of the menstrual cycle during resting heat exposure, as well as during exercise.^[48] Gruzca et al.^[100] also found a greater gain in sweating during the mid-luteal phase, although the menstrual cycle phase of their ten study participants was not verified

by hormone measurements. Most research, however, found no change in thermosensitivity over the menstrual cycle.^[17,49,52,98]

To detect possible changes in thermosensitivity and thermoregulatory thresholds, the responses of rectal temperature (T_{re}) and mean skin temperature (T_{sk}) to exercise and/or heat stress may be investigated. When looking at the slope of the temperature responses over time, the previously mentioned changes in thermosensitivity throughout the menstrual cycle were confirmed. Hessemer and Bruck^[48] studied the responses to 15 minutes of exercise at 70% $\dot{V}O_{2max}$ at an ambient temperature of 18°C and found a steeper slope for T_{re} during the early-follicular phase. These authors speculated that the temperature difference between early-follicular and mid-luteal phases would decrease further during exercise of longer duration. This would imply that at the end of long duration exercise the temperature difference between the phases of the menstrual cycle may disappear. Pivarnik et al.,^[51] reported opposite findings during 60 minutes of exercise at 65% $\dot{V}O_{2max}$ at moderate temperature (22°C). These authors found that T_{re} continually increased during the mid-luteal phase (up to 38.9°C at the end of exercise). Thus, study participants failed to reach a thermal equilibrium during the mid-luteal phase. During the mid-follicular phase, Pivarnik et al.^[51] found that T_{re} reached a plateau at 38.3°C. In contrast to these two studies, most other studies found no change in the rate of increase in T_{re} over the menstrual cycle.^[17,49,52,98]

Conflicting findings are also reported for mean T_{sk} responses to exercise and/or heat stress. Several studies found that mean T_{sk} at rest and during exercise did not show any changes over the menstrual cycle.^[49,51,98] Others showed that mean T_{sk} was higher during the mid-luteal phase at rest and during exercise.^[17,52]

In summary, most studies showed that the increased BBT during the luteal phase remained elevated throughout exercise and/or heat stress. Many also reported increased core temperature thresholds for thermoregulatory effector responses. These findings support the theory that the thermoregulatory

setpoint is increased during the luteal phase. Furthermore, most studies found no change in thermosensitivity and in mean T_{sk} responses to exercise and/or heat stress over the menstrual cycle.

4.2 Prolonged Exercise Performance

Increased body temperature during the luteal phase may result in increased thermoregulatory and cardiovascular strain. This may, in turn, have a negative effect on prolonged exercise performance during the luteal phase.

During sub-maximal aerobic exercise, most studies have found no changes over the menstrual cycle for $\dot{V}O_2$,^[38,40,41,44,47,51,58,68,69] heart rate^[38,41,44,47,68,69] and ratings of perceived exertion (RPE).^[41,47,58,68,69] William and Krahenbuhl^[75] found no difference in $\dot{V}O_2$ during exercise at 55% of $\dot{V}O_{2max}$, but during exercise at 80% of $\dot{V}O_{2max}$ a higher $\dot{V}O_2$ was found during the mid-luteal phase. Hessemer and Bruck^[48] reported a similar increased $\dot{V}O_2$ for the mid-luteal phase during exercise at 70% of $\dot{V}O_{2max}$, accompanied by a higher heart rate. Pivarnik et al.^[51] also found a higher heart rate for the mid-luteal phase during exercise at 65% of $\dot{V}O_{2max}$. These three thorough studies all found an increase in $\dot{V}O_2$ and/or heart rate during the mid-luteal phase, indicating a higher cardiovascular strain. The higher RPE found during the mid-luteal phase in the study by Pivarnik et al.^[51] after 50 minutes of exercise, confirms a subjective feeling of higher exertion during this phase. The increased cardiovascular strain, in particular the increased heart rate, during the mid-luteal phase is likely to be related to the increased body temperature during this phase. It could therefore be speculated that the potentially increased cardiovascular strain during the mid-luteal phase may lead to a decrease in prolonged exercise performance.

When investigating exercise performance, measured as time to exhaustion at 70% of $\dot{V}O_{2max}$, most studies have reported no significant changes over the menstrual cycle.^[40,68,69] McCracken et al.^[15] and Lebrun et al.^[32] also found that time to exhaustion at 90% $\dot{V}O_{2max}$ was not affected by the menstrual cycle. Jurkowski et al.,^[44] however, reported an increased time to exhaustion at 90% of $\dot{V}O_{2max}$ during

the mid-luteal phase. As previously mentioned, these results may be questioned based on uncertainty about the ovulation status of the study participants.

A major limitation of the time to exhaustion test at sub-maximal exercise intensities is the poor reproducibility. Beidleman et al.^[69] reported that the variability in their test of exercise time to exhaustion at 70% $\dot{V}O_{2max}$ was higher than anticipated, thus reducing the chance of showing a significant difference. McLellan et al.^[104] reported a large variability in exercise time to exhaustion at 80% $\dot{V}O_{2max}$, while Jeukendrup et al.^[105] found a very large (26.6%) coefficient of variation for the exercise time to exhaustion test at 75% of $\dot{V}O_{2max}$. Jeukendrup et al.^[105] stated that studies using these exercise time to exhaustion tests often concluded that "there is no effect", when these studies should have concluded that "it was not possible to detect an effect". This same statement may apply to studies that showed no effect of the menstrual cycle on performance, measured as time to exhaustion at sub-maximal exercise intensities.

Thus, even though most studies found no change over the menstrual cycle for $\dot{V}O_2$, heart rate and RPE, some studies suggested an increased cardiovascular strain during the luteal phase. Nevertheless, exercise performance, measured as time to exhaustion at sub-maximal intensities, showed no change over the menstrual cycle. These findings should be questioned due to the poor reproducibility of these performance tests.

4.3 Prolonged Exercise Performance in the Heat

As suggested in section 4.2, increased body temperature during the luteal phase may result in increased thermoregulatory and cardiovascular strain and a decrease in prolonged exercise performance. This potential negative effect of the luteal phase on prolonged exercise performance would be expected to be even greater when an extra heat stress is applied.

Many early studies have examined cardiovascular and thermoregulatory responses to sub-

maximal exercise in the heat over the menstrual cycle. However, only a few studies with hormone verification have conducted further investigations in this area. No changes were found over the menstrual cycle for cardiovascular responses (heart rate and/or $\dot{V}O_2$) to exercise in the heat at 20%,^[52] 30%,^[5] and 60% $\dot{V}O_{2\max}$.^[49] Thus, the menstrual cycle does not seem to affect cardiovascular responses to sub-maximal exercise in the heat. It should be pointed out that exercise was conducted at relatively low exercise intensities in these studies, and that in moderate conditions an increased cardiovascular strain during the mid-luteal phase was shown at higher intensities (70% and 65% of $\dot{V}O_{2\max}$).

The major limiting factor, when investigating exercise time to exhaustion in the heat, is expected to be the elevated core temperature during the luteal phase. Findings of several studies have suggested that exercise in hot conditions was limited by a critical core temperature^[73,106,107] and that a decreased initial core temperature had a positive effect on prolonged exercise performance.^[107,108] Only Tenaglia et al.^[52] have examined the effect of possible thermoregulatory changes over the menstrual cycle on exercise time to exhaustion in the heat. These authors found a longer time to exhaustion in the early-follicular phase during light intensity intermittent exercise. The testing in this study was conducted in uncompensable heat, which occurs when the maximum cooling capacity of the environment is smaller than the cooling required by the individual. Tenaglia et al.^[52] reported the expected higher T_{re} for the mid-luteal phase of the menstrual cycle at the start of exercise. These authors also found that there was no difference over the menstrual cycle for the rate of increase of T_{re} during exercise and for T_{re} at exhaustion. Because the initial T_{re} was lower during the early-follicular phase and increased at the same rate as in the mid-luteal phase, it took a longer time to reach the critical T_{re} at exhaustion.

Thus, if it is assumed that there is a critical core temperature limit for exercise performance, then elevated body temperature during the luteal phase will be a disadvantage and will limit exercise time to exhaustion in the heat. However, this has so far only

been shown during light intermittent exercise in uncompensable heat. Since higher exercise intensities in moderate conditions have already been associated with increased cardiovascular strain during the mid-luteal phase in moderate conditions, it could be speculated that the mid-luteal phase will have an even greater negative effect on prolonged exercise performance at moderate intensity in hot conditions. Further research is warranted to investigate this speculation.

Practical recommendations, particularly for regularly menstruating female endurance athletes, result from these findings. These athletes may be advised to adjust the competition schedule to their menstrual cycle, especially when competition is expected to take place in hot, humid conditions. Furthermore, the potential negative effects of the luteal phase of the menstrual cycle on work performance of women working for extended periods in hot, humid conditions will need to be considered. As a result, guidelines for work under heat stress may need to be adjusted for menstrual cycle phase.

5. Conclusions

This literature review focused on the potential effects of the menstrual cycle on muscle contractile characteristics, $\dot{V}O_{2\max}$ and prolonged exercise performance including temperature regulation. Besides the usual study design considerations, such as test protocol and number of study participants, several additional factors need to be taken into account when reviewing menstrual cycle research. The most important factor is the method of menstrual cycle phase verification. The measurement of estrogen and progesterone concentration is the gold standard in menstrual cycle research. Even when hormone concentrations are measured, differences in the timing of testing throughout the menstrual cycle, the high inter- and intra-individual variability in estrogen and progesterone concentration and the pulsatile nature of their secretion are likely to cause inclusion of a very large range in hormone levels within the same study group (i.e. same menstrual cycle phase). In addition, the interaction between estrogen and progesterone will influence their se-

condary effects, especially during the mid-luteal phase. The combination of these factors may easily obscure possible effects of female hormone fluctuations during the menstrual cycle on exercise performance.

The literature was found to be inconsistent regarding the effect of the menstrual cycle on muscle contractile characteristics, mainly due to methodological limitations. Even when these were overcome by using electrical stimulation to ensure maximal neural activation, conflicting findings were found. Most studies with hormone verification found no change in muscle strength and fatigability over the menstrual cycle. Thus the current literature suggests that fluctuations in female reproductive hormones throughout the menstrual cycle do not affect muscle contractile characteristics. For regularly menstruating female athletes in strength-specific sports, these findings indicate that there is no need for menstrual cycle adjustment to maximise competitive ability.

The menstrual cycle may affect $\dot{V}O_{2\max}$ through possible secondary effects of estrogen and progesterone on fuel availability, the oxygen transport system and \dot{V}_E .

A potential glycogen sparing effect of estrogen may decrease lactate response to exercise during the mid-luteal phase, as found in some studies. Most research, however, reported no effect of the menstrual cycle on lactate response to exercise.

Potential secondary effects of estrogen and progesterone on fluid regulation may influence determinants of the oxygen transport system and $\dot{V}O_{2\max}$ via changes in bodyweight, plasma volume, haemoglobin concentration and heart rate. Most studies with hormone verification found no significant change in bodyweight, plasma volume, haemoglobin concentration and haematocrit over the menstrual cycle. Some large studies, without hormone verification but with daily measurements, found a peak in fluid retention around ovulation and an increase throughout the second half of the luteal phase. The fact that these studies tested on many occasions throughout the menstrual cycle and reported this same pattern in fluid regulation warrants

further investigation into this area. Ideally, further research should consist of daily resting measures of estrogen, progesterone, and fluid regulating hormones, in particular aldosterone, as well as plasma volume, haematocrit and haemoglobin concentration and perhaps red cell production or red cell life span. Once a resting pattern over the menstrual cycle is established, the best timing for investigation of potential effects of fluid regulation on exercise performance can be determined.

Several studies found an increase in heart rate during the mid-luteal phase, which may be related to the increased body temperature at that time. Most studies, however, indicate that heart rate is not affected by the menstrual cycle.

Also for \dot{V}_E , several studies showed an increase during the mid-luteal phase, especially at rest and during low intensity exercise, potentially related to a central effect of progesterone. Most research, however, suggests that \dot{V}_E during exercise is not affected by the menstrual cycle.

Although inconsistencies in the literature were found, most studies indicate that the menstrual cycle does not affect lactate response to exercise, bodyweight, haemoglobin concentration, heart rate and \dot{V}_E . As these determinants of $\dot{V}O_{2\max}$ are unlikely to change over the menstrual cycle, it is not surprising that most studies found that $\dot{V}O_{2\max}$ is not affected by the menstrual cycle. This finding indicates that regularly menstruating female athletes, competing in intense anaerobic/aerobic sports, do not need to adjust for menstrual cycle to maximise performance.

It is evident that the menstrual cycle affects temperature regulation. An increased resting core temperature during the luteal phase is accompanied by increased core temperature thresholds for thermoregulatory effector responses. The increased luteal phase temperature at rest therefore remains elevated throughout exercise and/or heat stress, supporting the increased thermoregulatory setpoint theory. With regard to thermosensitivity and the rate of increase in T_{re} over the menstrual cycle, most research reported no change over the menstrual cycle.

Most research suggested that $\dot{V}O_2$, heart rate and RPE responses to sub-maximal steady state exercise were not affected by the menstrual cycle. At moderate exercise intensities, however, several studies found a higher cardiovascular strain in the mid-luteal phase.

The thermoregulatory and potential cardiovascular changes over the menstrual cycle are, in turn, likely to affect prolonged exercise performance. Research on exercise time to exhaustion, as a possible indicator of prolonged exercise performance, showed that in moderate conditions, time to exhaustion was not affected by menstrual cycle phase. The significance of this finding should be questioned due to the low reproducibility of the time to exhaustion test at sub-maximal exercise intensities. A more reproducible test of prolonged exercise performance may reveal a negative effect of the mid-luteal phase due to a possible increased cardiovascular strain.

In hot conditions, a decrease in exercise time to exhaustion was shown during the mid-luteal phase at light exercise intensity. It was suggested that, based on a critical temperature limit for exercise performance, the elevated body temperature during the mid-luteal phase limited prolonged exercise performance. The potential negative effects of the mid-luteal phase on prolonged exercise performance through elevated body temperature and potential increased cardiovascular strain may be more pronounced at moderate exercise intensities, especially in hot conditions. Further research in this area is recommended to investigate this speculation.

Practical implications of these findings for female endurance athletes may be to adjust the competition schedule to their menstrual cycle, especially when competition is expected to take place in hot, humid conditions. Furthermore, women working for extended periods in hot, humid conditions may need to consider potential negative effects of the luteal phase of the menstrual cycle on work performance and possible remedies.

The ultimate goal of understanding the complex mechanisms underlying variations in exercise performance throughout the menstrual cycle is to allow

the development of safe strategies for maximising exercise performance. The characterisation of hormonal profiles in distinct menstrual cycle phases, their physiological outcomes, and their effects on exercise performance indicators, is of vital importance to the success of these strategies. The status of the current research indicates that female athletes do not need to adjust competition schedules to their menstrual cycle, when muscle contractile characteristics and $\dot{V}O_{2\max}$ are the main performance determinants in their sport. For female endurance athletes, however, it may be advisable to adjust their competition schedule to their menstrual cycle, especially when competition is expected to take place in hot, humid conditions. To enable better understanding and as a result more practical advice, further research on the effect of the menstrual cycle on several aspects of, especially prolonged, exercise performance is warranted.

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Correspondence and offprints: *Xanne A.K. Janse de Jonge*, 12 Gilmore Road, Casula, NSW 2170, Australia.
E-mail: x.jansedejonge@uws.edu.au