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SYSTEMATIC REVIEW

The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis

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Abstract

Background Concentrations of endogenous sex hormones fluctuate across the menstrual cycle (MC), which could have implications for exercise performance in women. At present, data are conflicting, with no consensus on whether exercise performance is affected by MC phase.

Objective To determine the effects of the MC on exercise performance and provide evidence-based, practical, performance recommendations to eumenorrheic women.

Methods This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Four databases were searched for published experimental studies that investigated the effects of the MC on exercise performance, which included at least one outcome measure taken in two or more defined MC phases. All data were meta-analysed using multilevel models grounded in Bayesian principles. The initial meta-analysis pooled pairwise effect sizes comparing exercise performance during the early follicular phase with all other phases (late follicular, ovulation, early luteal, mid-luteal and late luteal) amalgamated. A more comprehensive analysis was then conducted, comparing exercise performance between all phases with direct and indirect pairwise effect sizes through a network meta-analysis. Results from the network meta-analysis were summarised by calculating the Surface Under the Cumulative Ranking curve (SUCRA). Study quality was assessed using a modified Downs and Black checklist and a strategy based on the recommendations of the Grading of Recommendations Assessment Development and Evaluation (GRADE) working group.

Results Of the 78 included studies, data from 51 studies were eligible for inclusion in the initial pairwise meta-analysis. The three-level hierarchical model indicated a trivial effect for both endurance- and strength-based outcomes, with reduced exercise performance observed in the early follicular phase of the MC, based on the median pooled effect size ($ES_{0.5} = -0.06$ [95% credible interval (CrI): − 0.16 to 0.04]). Seventy-three studies had enough data to be included in the network meta-analysis. The largest effect was identified between the early follicular and the late follicular phases of the MC ($ES_{0.5} = -0.14$ [95% CrI: − 0.26 to − 0.03]). The lowest SUCRA value, which represents the likelihood that exercise performance is poor, or among the poorest, relative to other MC phases, was obtained for the early follicular phase (30%), with values for all other phases ranging between 53 and 55%. The quality of evidence for this review was classified as "low" (42%).

Conclusion The results from this systematic review and meta-analysis indicate that exercise performance might be trivially reduced during the early follicular phase of the MC, compared to all other phases. Due to the trivial effect size, the large between-study variation and the number of poor-quality studies included in this review, general guidelines on exercise performance across the MC cannot be formed; rather, it is recommended that a personalised approach should be taken based on each individual's response to exercise performance across the MC.

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Extended author information available on the last page of the article

Key Points

In women, exercise performance might be reduced by a trivial amount during the early follicular phase of the menstrual cycle when compared with other phases. However, large between-study variance was identified, indicating that research design, participant characteristics and choice of outcome measure might influence any group-level effect.

Practically, the current evidence does not warrant general guidance on modulating exercise across the menstrual cycle. As such, we recommend that a personalised approach should be taken based on each individual's response to exercise performance across the menstrual cycle.

The quality of evidence for this review was mostly classified as "low" quality, which can be attributed to a range of methodological issues. Future studies need to improve methodological quality and limit confounders to facilitate a deeper understanding of the effects of the menstrual cycle on exercise performance.

1 Background

Over the last three decades, there has been a rise in the number of women participating in exercise, from physical activity to elite sport, attributable to the increasing development of, and investment in, women's professional sport [1–4]. Specifically, the percentage of women competing at the Olympic Games has increased from 26% in Seoul in 1988 to 45% in Rio de Janeiro in 2016 [5]. Furthermore, Tokyo 2021 is set to be the most sex-balanced Games in history, with the same number of medals available for men and women, which is projected to see women participation in the Games rise to 49% [5]. Performance-based research in women has not kept pace with the exponential rise in participation [6, 7]. Indeed, it would be naive to assume that all research in men can be directly applied to women, given the anatomical, physiological and endocrinological differences between the sexes [4, 8–10]. As such, sportswomen will benefit from sex-specific research and guidelines, which consider the effects of women's physiology, such as the menstrual cycle (MC), on performance [8, 11].

The MC is an important biological rhythm, whereby large cyclic fluctuations in endogenous sex hormones, such as oestrogen and progesterone, are observed [12–14]. The fairly predictable (and measurable) fluctuations in oestrogen and progesterone across the MC create significantly different transient hormonal profiles, which are used to differentiate between MC phases [15, 16]. As such, the MC is commonly divided into three phases, (1) the early follicular phase, characterised by low oestrogen and progesterone, (2) the ovulatory phase, characterised by high oestrogen and low progesterone, and (3) the mid-luteal phase, characterised by high oestrogen and progesterone [17]. Although the primary function of these hormones is to support reproduction, research has highlighted that the changing concentrations of oestrogen and progesterone across the MC also exert a myriad of diverse and complex effects on multiple physiological systems, including cardiovascular, respiratory, metabolic and neuromuscular parameters [12, 18, 19], which could have subsequent implications for exercise performance [15, 20–23].

There are a range of suggested mechanisms by which the cyclical fluctuations in oestrogen and progesterone across the MC might affect performance. Specifically, oestrogen is thought to have an anabolic effect on skeletal muscle [24, 25] and has been shown to play a role in substrate metabolism changes through increased muscle glycogen storage and increased fat utilisation [26]. Additionally, progesterone is thought to have anti-oestrogenic effects [21]. As such, it is plausible that changes in exercise performance might be observed due to the different hormonal profiles across the MC [15, 20–23]. To date, the effects of fluctuations in oestrogen and progesterone across the MC on exercise performance are conflicting, with studies reporting improved performance outcomes during the early follicular [27–29], ovulatory [30] and mid-luteal [31, 32] phases; whereas, others have shown no changes in exercise performance between MC phases [33–39]. Therefore, it is evident that a consensus is yet to be reached regarding the effects of the MC on exercise performance. Subsequently, no evidence-based guidelines for managing exercise performance across the MC currently exist for either exercising women, nor for practitioners working with elite sportswomen.

Given the recent increase in the number of women participating in exercise and the lack of consensus regarding the effects of the MC on exercise performance, there is a growing need to determine the effects of the fluctuations in oestrogen and progesterone across the MC on exercise performance. To our knowledge, this is the first meta-analysis to critically examine existing studies investigating changes in exercise performance across the MC, in eumenorrheic women. Additionally, this review is the first of its kind to appraise the quality of previous studies using robust assurance tools. The information provided by this meta-analysis can be used to inform practical recommendations for athletes, practitioners and researchers interested in managing exercise performance across the MC.

2 Methods

This review conforms to the PRISMA statement guidelines (see Electronic Supplementary Material Appendix S1) [40].

2.1 Study Inclusion and Exclusion Criteria

Consideration of Population, Intervention, Comparator, Outcomes and Study design (PICOS) was used to determine the parameters within which the review was conducted:

2.1.1 Population

Participants included healthy women who were (a) between the ages of 18 and 40 years; (b) eumenorrheic; (c) not taking any hormonal contraceptives or medication known to affect the hypothalamic–pituitary–ovarian (HPO) axis; (d) free from any menstrual-related dysfunctions (such as, amenorrhea) or any other conditions (e.g., pregnancy, eating disorders or disordered eating) known to affect the HPO axis; and (e) free from any injury that would affect participation. No restrictions were placed on activity level or training status.

2.1.2 Intervention

No specific intervention was investigated, but all participants were required to have a normal MC, defined as having a minimum of nine cycles per calendar year and a MC that ranged between 21 and 35 days in length.

2.1.3 Comparator

Comparisons were made between the early follicular phase (acting as a 'control' phase) of the MC and all other MC phases, in line with the following predetermined MC phase classification as shown in Fig. 1: early follicular (days 1–5), late follicular (days 6–12), ovulation (days 13–15), early luteal (days 16–19), mid-luteal (days 20– 23) and late luteal (days 24-28).

2.1.4 Outcomes

The primary outcome was exercise test performance. For the purposes of this review, exercise test performance was defined as total work done, time to completion, time to exhaustion, mean, peak and ratio outputs, rate of force production and decline, and indices of fatigue. Although maximum oxygen uptake (maximal [$\dot{V}O_{2max}$] or peak [$\dot{V}O_{2peak}$]) is not a performance test, this physiology-based outcome was included as it can be used as an indicator of performance. A full list of considered outcomes can be found in Electronic Supplementary Material Appendix S2. Performance outcome data were allocated into broad categories to allow for subgroup analysis; namely endurance (power and capacity) and strength (maximal expression of force and rate of force development). All exercise outcomes were extracted, and effect size duplication of multiple outcomes from the same test accounted for within the statistical analysis, as described below.

2.1.5 Study Design

Experimental studies were considered for analysis if they met the following inclusion criteria: (a) published, in full,

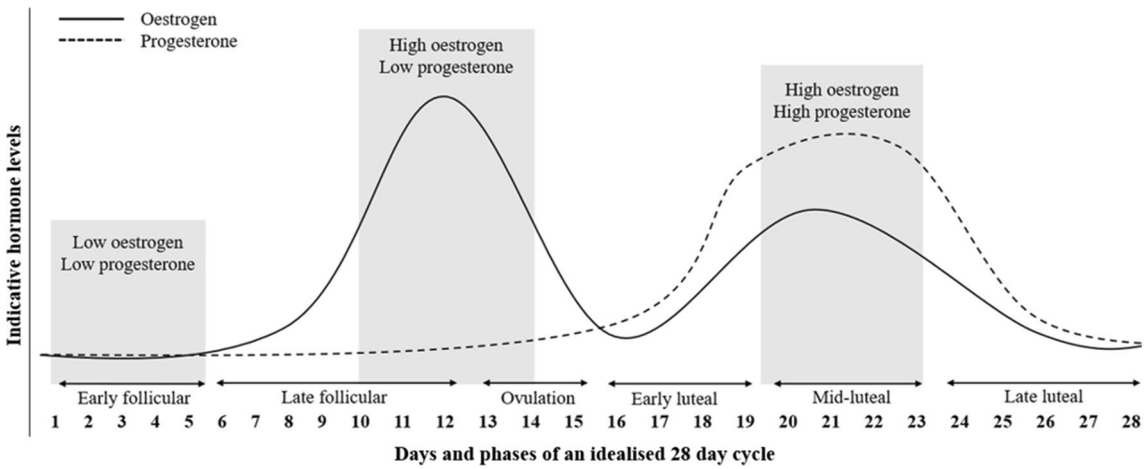

Fig. 1 Schematic displaying the hormonal fluctuations across an idealised 28-day menstrual cycle, with ovulation occurring on day 14 Adapted from Pitchers and Elliott-Sale [8]

in a peer-reviewed journal, (b) had the primary or secondary objective of assessing changes in exercise performance across the MC, (c) included within-group comparisons and (d) outcome measure(s) were taken in two or more defined MC phases. As such, case studies, review articles, study protocol papers and conference abstracts were excluded. Moreover, only full texts that were published in English or had an existing translation were retrieved and examined. There was no limit on date of publication.

2.2 Search Strategy for Identification of Studies

A systematic electronic literature search was conducted by KLM to identify all relevant articles using four online databases (PubMed, CENTRAL, SPORTDiscus and ProQuest). The searches were performed using medical subject headings terms, free-text and thesaurus terms, as well as, keywords from existing relevant papers [15, 20–23]. The following search terms and their combinations were used: ('menstrual cycle', OR 'menstrual phase', OR 'follicular phase', OR 'luteal phase') AND ('strength', OR 'power', OR 'torque', OR 'force', OR 'neuromuscular', OR 'max* voluntary contraction', OR 'isometric', OR 'isokinetic', OR 'skeletal muscle' OR 'muscular performance', OR 'aerobic', OR 'aerobic power', OR 'aerobic capacity', OR 'endurance', OR 'endurance power', OR 'endurance capacity', OR 'anaerobic', OR 'anaerobic power', OR 'anaerobic capacity', OR 'athletic performance', OR 'sports performance'). An example of a full electronic search for one database (PubMed: 14/01/2019) is presented in Electronic Supplementary Material Appendix S3. Databases were searched from inception until February 2019. The reference lists of obtained relevant articles and review articles were hand-searched to identify any further studies and were added in manually. Following the same search criteria and strategy, an updated electronic and manual hand-search for relevant literature was subsequently conducted in April 2020 to identify any further articles published between February 2019 and April 2020.

2.3 Data Selection, Extraction and Study Quality Assessment

2.3.1 Selection of Studies

Three reviewers (KLM, KMH and KES) independently reviewed the titles, abstracts and full-text paper of the identified articles for inclusion and any duplicates were removed, using Covidence systematic review software (v1251, Veritas Health Innovation, Australia). All searches followed a two-phase screening strategy. Phase one assessed the eligibility of the title and abstract of every manuscript generated from the electronic searches and hand-searching against the predetermined inclusion and exclusion criteria. Studies that either clearly did not meet the inclusion criteria or met at least one exclusion criterion were excluded at this phase. In phase two, the full-text paper was retrieved for the articles identified in stage one and assessed against the predetermined inclusion and exclusion criteria. Any conflicts between the reviewers relating to study eligibility were resolved in consensus meetings (KLM, KMH and KES).

2.3.2 Data Extraction and Management

Data extraction was conducted by one reviewer (KLM), using a pre-piloted data extraction form, and independently verified by two members of the review team (KMH and KES). Any discrepancies were resolved by reviewing the original article and consensus achieved by discussion during consensus meetings (KLM, KMH and KES), or, if needed, in consultation with a fourth reviewer (ED). When data were presented in graphical and not in numerical format, DigitizeIt software (v2.3, DigitizeIt, Germany) was used to convert the relevant data. Further, where data were incomplete, authors were contacted to obtain the relevant information. Authors were given 4 weeks to respond; if the authors failed to respond after this date, the papers were excluded if no relevant data could be extracted from the published version of the paper.

2.3.3 Quality Assessment of Included Studies

Study quality was assessed by one reviewer (KLM) and independently verified by two members of the review team (KMH and KES), using a strategy based on the recommendations of the Grading of Recommendations Assessment Development and Evaluation (GRADE) working group [41]. This strategy considers quality of evidence for any one outcome based on five domains, namely risk of bias, indirectness, inconsistency, imprecision or evidence of publication bias. Both risk of bias and indirectness were initially conducted at the individual study level, with mode ratings used to describe whole outcomes. The initial appraisal tool used was based on the Downs and Black checklist for measuring study quality [42] and was specifically modified for use in this review (see Electronic Supplementary Material Appendix S4). The modified Downs and Black checklist comprised 15 outcomes, from five domains: (1) reporting; (2) external validity; (3) internal validity—bias; (4) internal validity—confounding; and (5) power. A maximum attainable score of 16 could be awarded, whereby study quality was categorised as follows: "high" (14–16); "moderate" (10–13); "low" (6–9); or "very low" (0–5). The results of the Downs and Black assessment were used to assign an a priori quality rating to each study. This a priori rating was then either maintained, or downgraded a level, based on the response to two questions that were considered key to the *directness* of these

research studies: Q.1) was the MC phase confirmed using blood samples? If the authors reported using blood samples to confirm MC phase, the a priori rating was maintained and if not, the study was downgraded a level (*e.g.,* a study that started out as "high" in quality, but did not confirm MC phase using a blood sample, drops to "moderate" in quality); and Q.2) was the MC phase confirmed using urinary ovulation detection kits? If the authors reported the use of an urinary ovulation detection kit to identify MC phase, the Q.1 rating was maintained; if not, the study was downgraded a level (as such, the maximum rating for any study that does not use serum analysis or urinary ovulation detection kits to identify and verify MC phase is "low"). The inclusion of these specific questions was based on the methodological conclusions made in previous studies [10, 17]. Consistency was ascertained using the meta-analysis results and was based on visual inspection of effect size estimates, whether or not confidence intervals overlapped, and on statistical tests for heterogeneity. Precision was judged based on the number of outcomes available (with outcomes based on < 5 data points downgraded) and on visual analysis of the width of the confidence intervals. Publication bias was assessed using Egger's test along with visual inspection of funnel plots. Overall, this procedure allowed the final quality of evidence for each outcome to be categorised as either "high", "moderate", "low" or "very low" in quality. This quality appraisal was not used to exclude any study, although a sensitivity analysis was conducted using only those individual studies deemed to be of "high" or "moderate" quality, based on the risk of bias and directness assessments. Any differences between the reviewers were resolved by discussion during consensus meetings (KLM, KMH and KES), or, if needed, in consultation with a fourth reviewer (ED).

2.4 Data Synthesis

Data were extracted from studies comprising both between- and within-group designs. Pairwise effect sizes were calculated by dividing mean differences by pooled standard deviations. At the study level, variance of effect sizes was calculated according to standard distributional assumptions [43]. All meta-analyses were conducted within a Bayesian framework enabling the results to be interpreted more intuitively compared to a standard frequentist approach through use of subjective probabilities [44]. With a Bayesian framework, dichotomous interpretations of the results of a meta-analysis with regards to the presence or absence of an effect (e.g. with *p* values) can be avoided, and greater emphasis placed on describing the most likely values for the average effect and addressing practical questions such as, the probability the average effect is beyond a certain threshold [44]. The Bayesian framework is also particularly suited to hierarchical models and sharing information within and across studies to improve estimates [44]. In the present meta-analysis, three-level hierarchical models were conducted to account for covariance in multiple outcomes presented in the same study [45]. For the initial analysis, individual effect sizes were calculated by comparing exercise performance in the early follicular phase (acting as a 'control' phase) with all other phases of the MC (late follicular, ovulation, early luteal, mid-luteal and late luteal). Meta-regression was performed to assess whether the pooled effect size estimate was influenced by testing category (endurance or strength outcomes). Where no evidence of a difference was identified, the model was re-run combining both categories of outcomes to increase data to better estimate model parameters. Given the expectation of relatively small effect sizes, an a priori threshold of ± 2 was identified for outliers. Primary analyses were completed with outliers removed, but results were also presented from the full complement of studies as sensitivity analyses. A sensitivity analysis was also conducted on data obtained from studies categorised as "high" or "moderate" in quality. Assessment of publication bias was made using a multilevel extension of Egger's test with effect sizes regressed on the inverse of standard errors [46]. Inferences from all analyses were performed on posterior samples generated by Markov Chain Monte Carlo with Bayesian 95% credible intervals (CrIs) constructed to enable probabilistic interpretations of parameter values. Interpretations were based on visual inspection of the posterior sample, the median value ($ES_{0.5}$: 0.5 quantile) and 95% CrIs. Cohen's [47] standard threshold value of 0.8 was used to describe effect size as large, values between 0.5 and 0.8 as medium, values between 0.2 and 0.5 as small, and values between 0 and 0.2 as trivial.

Subsequent to this initial analysis, a network meta-analysis approach was used to compare exercise performance measured across all MC phases (early follicular, late follicular, ovulation, early luteal, mid-luteal and late luteal) with each other. Network meta-analyses are becoming increasingly common in evidence synthesis and are most commonly used to compare multiple experimental treatments where individual studies are unlikely to directly compare all relevant treatments [48]. The technique calculates pairwise effect sizes from studies comparing two treatments (direct evidence), and generates indirect evidence comparing other treatments through a common comparator [48]. The technique was adopted in the present review to supplement the initial pairwise meta-analysis and synthesise additional data comparing exercise performance using different combinations of MC phases. Study-specific treatment effects were drawn from multivariate normal distributions with up to five arms included. To test the consistency assumption of the network meta-analysis, the fit of the base-case model was compared to that of the inconsistency model. To summarise potential differences in exercise performance outcomes across all MC phases, results from the network meta-analysis were used to calculate the Surface Under the Cumulative

Ranking curve (SUCRA; [49]). For each MC phase, a SUCRA value expressed as a percentage was calculated representing the likelihood that exercise performance was maximised or near maximised relative to other MC phases. More formally, the SUCRA value can be interpreted as the average proportion of phases where exercise performance is lower than the phase considered, with the mean SUCRA value equal to 50% [50]. Analyses were performed using the R packages R2WinBUGS [51] and brms [52]. Convergence of parameter estimates was checked with Gelman–Rubin R-hat values [53].

3 Results

3.1 Literature Search

The literature search and selection of studies are presented in Fig. 2.

3.2 Study Characteristics

In total, 78 studies [19, 27–39, 54–117] with a total of 1193 participants were included in the review. Details of the included studies are shown in Electronic Supplementary Material Appendix S5.

3.3 Methodological Quality

3.3.1 Quality Assessment of Included Studies

All quality classifications are presented in Fig. 3. Analysis of quality based on the entire evidence base ($n = 78$) was ascertained at the individual study level, and according to the Downs and Black checklist, as well as the additional questions regarding MC phase confirmation. The quality of the evidence from the 78 studies included in this review was primarily classified as "low" in quality (8% "high"; 24% "moderate"; 42% "low"; 26% "very low"; Fig. 3) such that, "our confidence in the effect estimate is limited: the true effect might be substantially different from the estimate of the effect" [118]. In particular, 71% of studies were initially allocated an a priori rating of "moderate" quality; however, following the application of questions pertaining to MC phase identification and verification, only 24% of these studies were allocated a final rating of "moderate" quality.

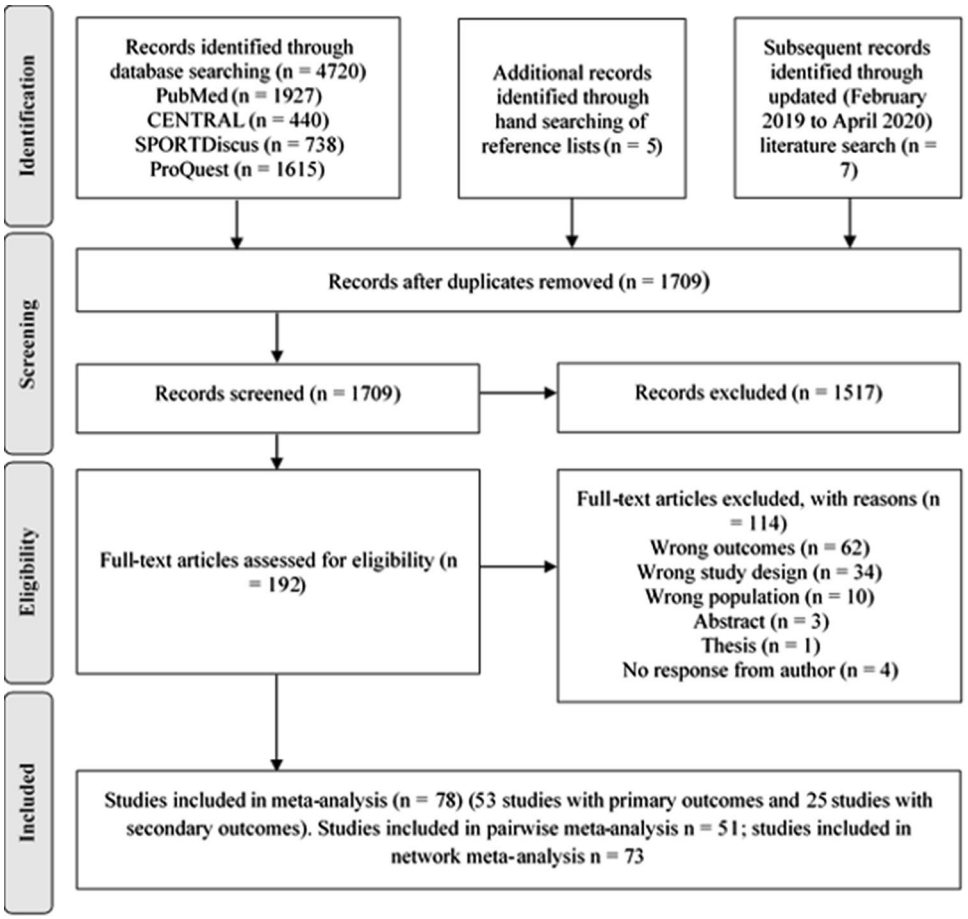

Fig. 2 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines flow chart for literature search and study selection

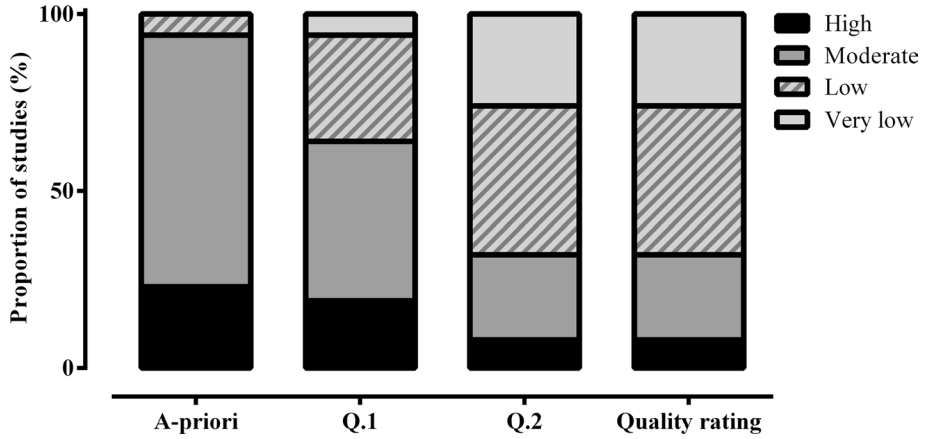

Fig. 3 Quality rating of outcomes from all included studies ($n=78$). Each bar represents the proportion of studies assigned a "high," "moderate," "low," or "very low" quality rating. The *x*-axis represents the different stages of the quality appraisal process, with question one (Q. 1) and question two (Q. 2) indicating the questions asked to determine menstrual cycle phase identification and verification in each study, with the final bar representing the proportion of studies assigned to each quality rating category

3.3.2 Menstrual Cycle Phase Identification and Verification

In the 78 included studies, an array of methods was used to identify MC phase: (1) a combination of methods (*e.g.* counting of days, basal body temperature [BBT], assessment of menstrual symptoms, MC history and serial follicular scanning] without urinary ovulation detection kits (45%); (2) a combination of methods (e.g. counting of days, BBT, MC history, assessment of menstrual symptoms and urine ovulation detection kits) with urinary ovulation detection kits (31%); (3) counting of days (10%); (4) MC history (4%); (5) BBT (4%); and (vi) urinary ovulation detection kits (1%). In addition, some studies (5%) did not provide any information on how MC phases were identified. In relation to MC phase verification, out of the 78 studies included in the review, the majority of studies (59%) retrospectively verified MC phase using serum oestrogen and progesterone, a small number of studies retrospectively verified MC phase using saliva (4%) or urine (2%) oestrogen and progesterone, and the remaining studies provided no information on how they verified the identified MC phase (35%).

3.4 Outcomes

3.4.1 Analysis 1: Pairwise Meta-Analysis

The initial meta-analysis comprised pooling of pairwise effect sizes comparing exercise performance during the early follicular phase of the MC with all other MC phases (late follicular, ovulation, early luteal, mid-luteal and late luteal). From the 78 studies that were eligible for the systematic review, 51 studies [19, 27–29, 31, 34–37, 54–60, 62–67, 70–72, 74, 75, 77, 78, 81, 84–86, 89–94, 96, 99, 101–103, 105–107, 109, 114–116] included assessment of exercise performance during the early follicular phase of the MC and included all other data required for calculations. The 51 studies (mode quality rating = "low"; 8% "high"; 24% "moderate"; 37% "low"; 31% "very low") generated 362 pairwise effect sizes (240 strength and 122 endurance) with an average of four outcomes per study and a range from 1 to 12 outcomes. Data were obtained from 709 participants with studies comprising a mean participant size of 14 (range $n=5$–100). A total of nine outliers were identified (seven studies with effect sizes less than −2 [favoring the "other MC phases"] and two studies with effect sizes greater than +2 [favoring the early follicular phase]) and subsequently removed from the analysis. The three-level hierarchical model indicated a trivial effect with reduced performance obtained in the early follicular phase of the MC, based on the median pooled effect size ($ES_{0.5}=-0.06$ [95% CrI: − 0.16 to 0.04]; Fig. 4). Large between-study variance was identified ($\tau_{0.5}=0.26$ [0.18–0.38]) and interclass correlation coefficient estimates close to zero indicated little within-study correlation between outcomes. Pooling of strength and endurance outcomes was conducted as no evidence was obtained that indicated a differential effect between these performance categories ($ES_{0.5/\text{Endurance-Strength}}=-0.01$ [95% CrI: − 0.18 to 0.16]). Posterior estimates of the pooled effect size indicated close to zero probability of a small effect either in favour of the early follicular phase or all other MC phases ($d \geq 0.2$; $p \leq 0.001$). Egger's regression test provided no evidence of publication bias ($Egger_{0.5}=-0.01$ [95% CrI: − 0.09 to 0.08]). Inclusion of outliers within the model had minimal influence on the average effect size ($ES_{0.5}=-0.08$ [95% CrI: − 0.21 to 0.05]) and between-study variance ($\tau_{0.5}=0.30$

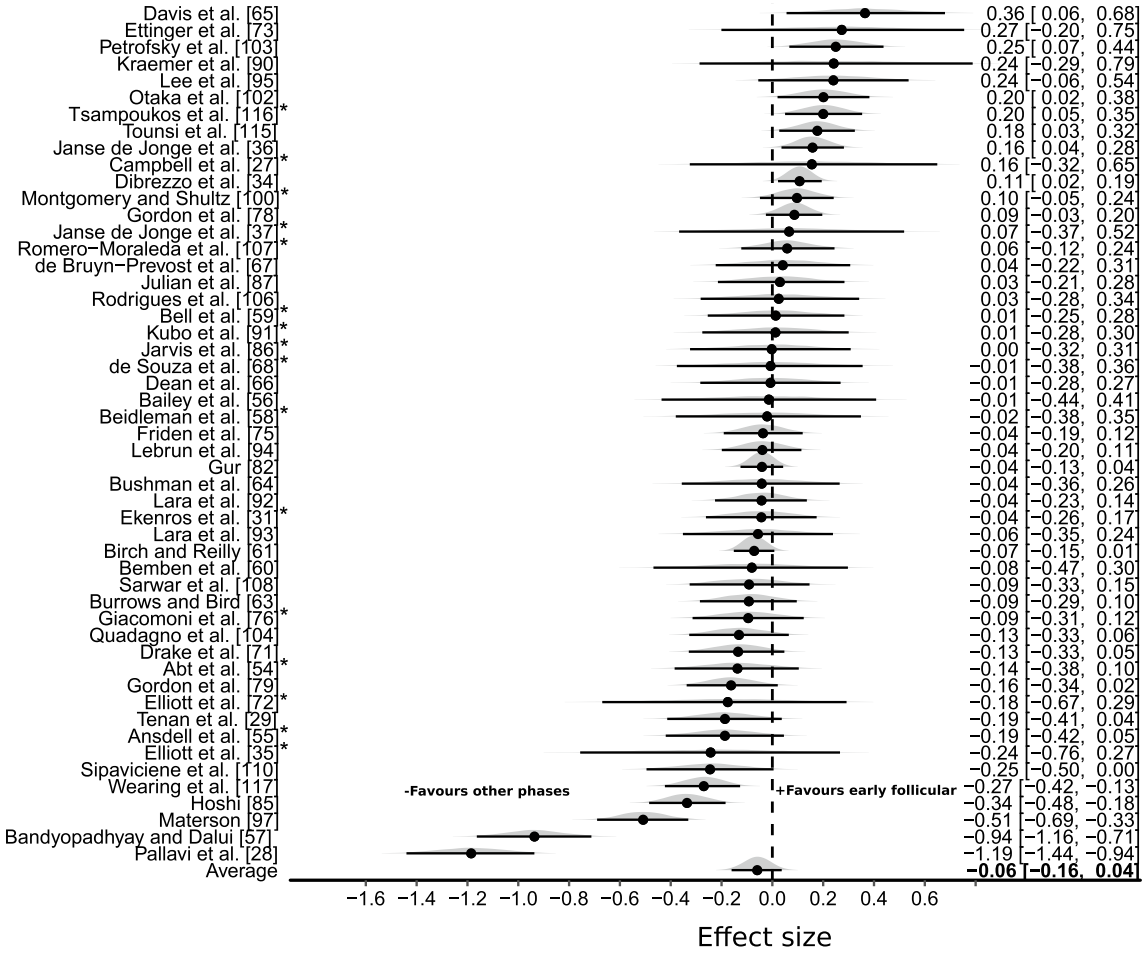

Fig. 4 Bayesian Forest Plot of multilevel meta-analysis comparing performance measured during the early follicular phase with all other menstrual cycle phases. The study-specific intervals represent individual effect size estimates and sampling error. The circle represents the pooled estimate generated with Bayesian inference along with the 95% credible interval (95% CrI). Negative values favour all other menstrual cycle phases (late follicular, ovulation, early luteal, mid-luteal and late luteal) compared to the early follicular phase. High and moderate quality studies are indicated with an asterisk (*)

[95% CrI: 0.23–0.39]). A sensitivity analysis was completed with data obtained from studies classified as either "high" or "moderate" in quality (16 studies compromising 38 strength effect sizes and 12 endurance effect sizes from 169 participants [19, 27, 31, 35, 37, 54, 57, 58, 67, 71, 75, 85, 90, 99, 106, 115]). Compared to the primary analysis, the reduced data set resulted in a relatively symmetric credible interval around the zero value ($ES_{0.5} = -0.01$ [95% CrI: − 0.11 to 0.08]).

3.4.2 Analysis 2: Network Meta-Analysis

Figure 5 shows a network diagram illustrating the pairwise effect sizes calculated across the six MC phases (early follicular, late follicular, ovulation, early luteal, mid-luteal and late luteal). Seventy-three studies (mode quality rating = "low"; 7% "high"; 26% "moderate"; 42% "low"; 25% "very low") included enough data to be included in the network meta-analysis [19, 27–29, 31, 33–39, 54–68, 70–72, 74, 75, 77–117]. A total of 220 performance outcomes were included across 954 participants, with the number of comparisons across MC phases equal to: comparison between two phases = 87; comparison between three phases = 93; comparison between four phases = 27; comparison between five phases = 10; and comparison between six phases = 3. The

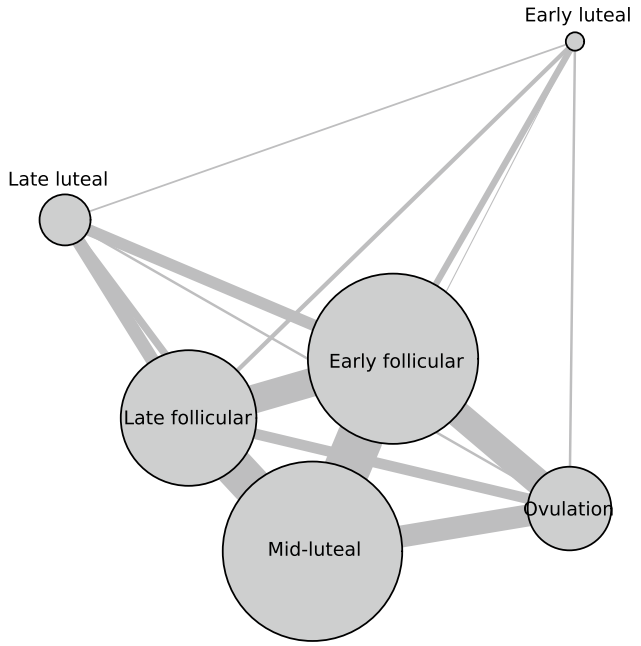

Fig. 5 Network diagram illustrating the pairwise effect sizes calculated across the six menstrual cycle phases (early follicular, late follicular, ovulation, early luteal, mid-luteal and late luteal). The analysis included direct and indirect pairwise effect sizes from 73 studies. The relative size of nodes and relative thickness of connecting lines illustrate the frequency of outcomes measured in a given menstrual cycle phase and the number of direct comparisons between two phases, respectively

Table 1 Summary of network meta-analysis results from 73 studies using the early follicular phase as a reference

Comparison to early follicular phase	Effect size [95% CrI]	SUCRA (%)
Early follicular	–	30
Late follicular	− 0.14 [− 0.26 to − 0.03]	54
Ovulation	− 0.07 [− 0.15 to 0.07]	55
Early luteal	− 0.07 [− 0.19 to 0.16]	54
Mid-luteal	− 0.04 [− 0.11 to 0.08]	55
Late luteal	− 0.01 [− 0.18 to 0.17]	53

Negative values for effect sizes favour all other menstrual cycle phases (late follicular, ovulation, early luteal, mid-luteal and late luteal) compared to the early follicular phase

SUCRA the surface under the cumulative ranking curve, *CrI* credible intervals

most frequent comparisons made were between the early follicular and mid-luteal phase of the MC (21% of comparisons), followed by the late follicular and mid-luteal phases of the MC (18% of comparisons). Pairwise estimates including the early follicular phase as a reference are presented in Table 1. with negative median pooled effect sizes ("other MC phases") obtained for all comparisons and the largest effect identified between the early follicular and the late follicular phase of the MC ($ES_{0.5} = -0.14$ [95% CrI: − 0.26 to − 0.03]). The lowest SUCRA value was obtained for the early follicular phase (30%) with all other MC phase values ranging between 53 and 55%.

4 Discussion

The aim of this review was to examine if MC phase affects exercise performance in eumenorrheic women. The results indicate that on average, exercise performance might be trivially reduced during the early follicular phase of the MC when compared with all other MC phases. Performance was consistent between all other MC phases. In addition to the estimated trivial average effect, results from the meta-analysis models showed relatively large between-study variance indicating that research design, participant characteristics and type of performance measured might influence any effect. Furthermore, most studies that were included in this meta-analysis were classified as "low" in quality, and as such, the confidence in the evidence reported in this meta-analysis is also low, and should be interpreted with caution. Due to the trivial effect size, the large between-study variation and the number of poor-quality studies included in this review, general guidelines on exercise performance across the MC cannot be formed; rather, it is recommended that a personalised approach should be taken based on each individual's response to exercise performance across the MC.

There are a range of suggested mechanisms by which the lower levels of oestrogen and progesterone seen in the early follicular phase of the MC might negatively affect the exercise performance. Although a detailed mechanistic review is beyond the scope of this review, the following points can be noted. First, oestrogen is known for its anabolic effects [24, 25], as well as its role in regulating substrate metabolism through increasing glycogen uptake and sparing glycogen stores. Additionally, it has been shown to have antioxidant and membrane stabiliser properties, which might offer protection against exercise-induced muscle damage and reduce inflammatory responses [26]. Further, oestrogen is thought to have neuroexcitatory effects, whereby it reduces inhibition and increases voluntary activation [19]. Therefore, when oestrogen rises during the late follicular and ovulatory phases and remains elevated in the mid-luteal phase, it is plausible that this might affect muscular performance [24, 25] or maximal and submaximal intensity exercise performance [26]. Moreover, progesterone is thought to have anti-oestrogenic effects [21]; therefore, it could be speculated that the beneficial performance effects of oestrogen are likely to be greater in the late follicular and ovulatory phases when

oestrogen is high without the interference of progesterone, compared to the mid-luteal phase when *both* oestrogen and progesterone are high. This speculation is supported by the finding presented here that the biggest difference in performance was between the early follicular and late follicular phases of the MC. However, the average effect calculated was trivial and there was considerable overlap between each of the pairwise comparisons with the early follicular phase. Whilst the current meta-analysis cannot identify the mechanisms responsible, it does indicate that, on average, exercise performance might be reduced by a trivial amount in the early follicular phase of the MC compared with all other phases. Interestingly, our sister meta-analysis, on the effects of oral contraceptives (OCs) on exercise performance, showed that, compared with eumenorrheic women, OC users have on average slightly inferior exercise performance [119]. Oral contraceptive use results in significantly downregulated concentrations of endogenous oestrogen and progesterone when compared with the ovulatory and mid-luteal phases of the MC [71]. Indeed, the endogenous hormonal profile of OC users is comparable to the profile seen during the early follicular phase of the MC [71]. Both meta-analyses show slightly impaired, group-level, exercise performance when *both* oestrogen and progesterone are at their lowest, therefore collectively suggesting that exercise performance might be mediated by the concentration of endogenous ovarian hormones in some exercising women.

Within the literature to date, the most common comparison used when investigating the effects of the MC on performance was between the early follicular and mid-luteal phase. This is not surprising, as the difference in the hormonal milieu is typically at its greatest between these phases (early follicular when *both* oestrogen and progesterone are low, and mid-luteal when *both* oestrogen and progesterone are high) [17]. As such, if performance was altered by synergistic fluctuations in oestrogen and progesterone levels, the comparison between these two phases would maximise the chance of observing an effect. This bi-phasic comparison, however, ignores the late follicular and ovulatory phases of the MC, when oestrogen is high, and progesterone is low. The network analysis indicated that the largest difference in performance might be expected between the early follicular and the late follicular phases of the MC, when *both* oestrogen and progesterone are low and when oestrogen rises without a concurrent increase in progesterone. Therefore, the effects of oestrogen, without the interference of progesterone, might be overlooked if the late follicular or ovulatory phases are not included within the phase comparisons. Future studies should, therefore, consider multiple phase comparisons so that the effects of different ratios of oestrogen and progesterone can be explored. It should be noted, however, that the inclusion of multiple phase comparisons will result in more variability, and as such, more participants will be needed to conclude any potential effects.

Although this systematic review included 78 studies and 1193 women (range $n = 5$–100), there were very few studies classified as "moderate" or "high" in quality, which implies that the confidence in the evidence used in this meta-analysis should be low. Specifically, only 24% of studies were allocated a quality rating of "moderate", and only 8% of studies were allocated a quality rating of "high". Our quality assessment approach included consideration of the methods used to identify and verify the MC phase in the included studies, which is considered to be key to the trustworthiness of the results obtained (i.e. Q1. was the MC phase confirmed using blood samples; Q2. was the MC phase confirmed using urinary ovulation detection kits?). Across the included studies there was large variability in the methods used to identify and then verify MC phase, namely calendar-based counting, BBT, MC history questionnaires, urinary ovulation detection kits, and salivary, urinary and serum measurement of both oestrogen and progesterone. Calendar-based counting is an indirect method to identify MC phase, whereby the self-reported onset of menses is set as day one, and the phases are then established by counting days from this point [17]. This method, however, assumes that all participants with regular menstruation experience ovulatory cycles with a mid-cycle peak in oestrogen, which is not always the case [120, 121]. As such, the use of calendar-based counting methods in isolation is not recommended when accurate identification of MC phase is required [122]. Similarly, BBT is a widely used method for identifying ovulation, and the length of the follicular and luteal phases [17], but this method does not provide information regarding actual hormone concentrations [123], and temperature readings might also be influenced by a range of factors such as illness, stress, sleep patterns and medication [124]; hence BBT in isolation is not considered a reliable method for MC phase verification [17]. Studies using these aforementioned methods were downgraded on this basis. Indeed, very few studies used a combination of the recommended methods by Cable and Elliott [10] and Janse de Jonge et al. [17], which include the use of the calendar-based counting method in conjunction with urinary ovulation detection kits to assist in setting the timing of testing throughout the MC and to confirm the presence of an ovulatory cycle, followed by serum measurement of both oestrogen and progesterone levels to subsequently verify the phases of the MC. Given that the rationale for exploring the effect of the MC on performance is underpinned by changes in oestrogen and progesterone, it is essential that studies should accurately verify the acute changes in endogenous hormones during each phase of the MC to ensure that the intended phase is being examined. Overall, without blood analysis, it is unclear which hormone milieu is being investigated, thus making it difficult to draw accurate conclusions

regarding changes in performance across the MC and to make direct comparisons between studies. These recommendations echo recent publications in the area of women's physiology [10, 17], demonstrating an increasing awareness for the nuances of this type of research, and collectively provide researchers with ample tools to make methodological decisions for future investigations. To limit the influence of low quality papers on the analyses, a sensitivity analysis was conducted with data obtained from studies that were classified as either "moderate" or "high" in quality [19, 27, 31, 35, 37, 54, 57, 58, 67, 71, 75, 85, 90, 99, 106, 115]. Due to the limited amount of data available, only the pairwise meta-analysis comparing exercise performance during the early follicular phase of the MC with all other MC phases was conducted. The sensitivity analysis provided no evidence of any effect, with a relatively symmetric credible interval centred close to zero. Whilst studies that were allocated a higher quality rating were better able to identify and verify the MC phase, there was no association between study quality and average sample size. Given the reduced amount of data included within the sensitivity analysis and the low sample sizes, the result is consistent with the primary analyses and conclusion that if an average effect exists, it is likely to be trivial in magnitude.

The results from the meta-analysis models consistently showed large between-study variance, which might be attributable to several factors: (a) inconsistent research design, as shown by the network analysis that highlights the discrepancy in the number of phase comparisons made between studies; (b) poor methodological practices, as emphasised by the quality assessment, whereby the majority of studies included in the meta-analysis were classified as "low" (42%) in quality primarily due to inadequate MC phase identification and verification in many studies; (c) non-homogenous participant groups, as shown in Electronic Supplementary Material Appendix S5 participants in this meta-analysis ranged from sedentary, to healthy, to physically active to elite athletes; and (d) large variation in the type of performance outcome measured, as detailed in Electronic Supplementary Material Appendix S2. As such, the breadth of this research area, without the corresponding depth, makes it difficult to apply a meaningful, yet generalisable, interpretation of the current data.

5 Conclusion

This is the first systematic review with meta-analysis to examine the effect of MC phase on exercise performance in eumenorrheic women. These data provide new information that exercise performance might on average be reduced by a trivial amount during the early follicular phase of the MC, compared with all other MC phases. The current meta-analysis also identified large between-study variance in the effect of the MC on exercise performance. This might have been influenced by a range of methodological factors and small participant numbers (average $n = 14$) as well as associated high sampling variance. Participant characteristics, such as training history, might also have contributed to the large between-study variance observed. From a practical perspective, as the effects tended to be trivial and variable between studies, the implications of these findings are likely to be so small as to be meaningless for most of the population. These trivial effects might, however, be of greater relevance to elite athletes, where the difference between winning and losing is marginal. Specifically, we recommend that practitioners working with elite sportswomen need to consider the MC and be aware of the potential times across the cycle whereby exercise performance might be reduced (early follicular phase) or enhanced (all other MC phases), but this approach should be tailored to, and informed by, the individual athlete. In the future, it would be interesting to identify which factors might cause some women to experience reduced performance during the early follicular phase of the MC when compared with all other MC phases, and identify strategies to monitor these effects. Therefore, future studies need to improve methodological quality (e.g., appropriate biochemical outcomes to confirm MC phase) and limit confounders to facilitate a deeper understanding of the effects of the MC on exercise performance in individuals.

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Availability of Data and Material Please contact the corresponding author for data requests.

Compliance with Ethical Standards

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The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis. Sports Medicine. Corresponding author: Dr Kirsty Elliott-Sale, Sport Health and Performance Enhancement (SHAPE) Research Centre, Department of Sport Science, Nottingham Trent University, Nottingham, UK. Email: kirsty.elliottsale@ntu.ac.uk.

Electronic Supplementary Material Appendix S1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2009 Checklist.

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3-4
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	4
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (*e.g.,* Web address), and, if available, provide registration information including registration number.	N/A
Eligibility criteria	6	Specify study characteristics (*e.g.,* PICOS, length of follow-up) and report characteristics (*e.g.,* years considered, language, publication status) used as criteria for eligibility, giving rationale.	4-5
Information sources	7	Describe all information sources (*e.g.,* databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	6
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	Electronic Supplementary File 3

Study selection	9	State the process for selecting studies (*i.e.,* screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	6-7
Data collection process	10	Describe method of data extraction from reports (*e.g.,* piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	6-7
Data items	11	List and define all variables for which data were sought (*e.g.,* PICOS, funding sources) and any assumptions and simplifications made.	4-6
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	7-8
Summary measures	13	State the principal summary measures (*e.g.,* risk ratio, difference in means).	5 and Electronic Supplementary File 2
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (*e.g.,* I^2) for each meta-analysis.	7-8
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	7-8
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	7-8
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	9
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	9 and Electronic Supplementary File 5
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	9-12
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	9-12
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	9-12

Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	9-12
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	9-12
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	13-15
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	13-15
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	15
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	16

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Electronic Supplementary Material Appendix S2. Full List of Considered Outcomes from the 78 Included Studies.

Considered outcome(s)
Strength
Hamstring:quadricep strength ratio at 60 and 180º s^{-1} [1]
Maximum voluntary contraction (N) with motor nerve stimulation [2]
Time to task failure (s) during fatiguing task involving sets of intermittent isometric contractions performed in the lower-body [2]
Peak isokinetic torque of the knee flexors and extensors at 1.05 and 3.14 $rad.s^{-1}$ through 90º range of motion on an isokinetic dynamometer (Nm) [3]
Maximal voluntary isometric contraction of the knee flexors and extensors measured at 0 $rad.s^{-1}$ and 60º of knee flexion with electrical stimulation (Nm) [3]
Rate of force production during a maximal voluntary isometric hamstring contraction ($N.s^{-1}$) [4]
Time to 50% peak force during a maximal voluntary isometric hamstring contraction (ms) [4]
Maximal isometric lifting strength (MILS) performed at both knee and waist height (N) [5, 6]
Time to volitional fatigue at 45% MILS performed at both knee and waist height (s) [5, 6]
Maximal acceptable load (kg) [5]
Handgrip strength (N) [7, 8, 9]
Standing long jump performance x body mass (kg.m) [7]
Mean peak torque of knee flexors and extensors at 60, 180, 240º.s (Nm) [10]
Muscular endurance and work ratios of knee flexors and extensors at 240º.s [10]
Maximal torque produced during an isometric muscle action (Nm) [11]
Torque produced at a sub-maximal (20, 50 and 75%) isometric muscle action (Nm) [11]
Peak isokinetic muscle torque of knee extensors at 120º.s (Nm) [12, 13]
Handgrip strength (kg) [12, 13, 14, 15, 16, 17]
Peak length of hop during a one-leg hop test (cm) [12, 13]
Maximum voluntary isometric force of the first dorsal interosseous (N) [18, 19]
Maximal jump power from a multi-jump test (W.kg) [20]
Maximal jump height from a squat jump test (cm) [20]
Torque production (Nm) of the knee extensors and flexors at 60, 80, 120 and 240º.s [21]
Torque ratios (peak and total work) during concentric and eccentric hamstring and quadriceps testing at 60 and 180º.s [22]
Peak torque of quadricep and hamstring flexors and extensors at 120º.s (Nm) [23]
Hamstring:quadricep strength ratio [23]

Time to task failure during a sustained isometric fatiguing contraction at 25% of MVC (s) performed in the upper-body [24]

Back lift strength (kg) [15]

Isometric quadricep strength (N) at 60º with electrical stimulation [8]

Isokinetic strength of the quadricep flexors and extensors at 60°.s^{-1} and 140º.s^{-1} (Nm) [8]

Time to fatigue during static handgrip at 40% of maximum (s) [16]

Counter movement jump height (cm) [25]

Maximal voluntary isometric strength of knee extensors and plantar flexors (Nm) with electrical stimulation [26]

Peak isokinetic torque of quadriceps and hamstrings at 30º.s (Nm) [27]

Force to flex the knee from 90° to 125° (N) [28]

Maximal voluntary isometric strength of the quadriceps and hamstrings (Nm.kg) [29]

Isometric hip strength (Nm) [30]

Work done during Mosso's Ergograph test (J) [17]

Endurance time at 20, 40 and 60% handgrip maximum strength (s) [31]

Bench press mean weight lifted (pounds) [32]

Leg press mean weight lifted (pounds) [32]

MVC (kg) during leg press exercise [33]

Mean and peak force at 20, 40, 60 and 80% of one-repetition maximum performed on a Smith Machine [34]

Maximum voluntary isometric strength of the quadriceps (N) [9]

Jump height (cm) from a drop jump [35]

Maximum isometric torque of knee extensor muscles (Nm) with electrical stimulation [35]

Maximum voluntary contraction (Nm) [36]

Mean time to task failure (s) during an endurance task [36]

Absolute performance during a five-jump test (m) [37]

Standing broad jump performance distance (inches) [38]

Maximum hip flexion and extension strength (pounds) [38]

Endurance

Cycling TTE at 70% $\dot{V}O_{2peak}$ (min) [39]

Queens College Step Test to predict $\dot{V}O_{2max}$ (ml.kg^{-}1.min^{-1}) [40]

Treadmill running TTE at a heart rate of 135–140 b.min^{-1} (min) [40]

$\dot{V}O_{2peak}$ (ml.kg-1.min-1) during a progressive-intensity, continuous, treadmill running test to exhaustion [41]

Treadmill running TTE at 70% $\dot{V}O_{2peak}$ (min) [41]

$\dot{V}O_{2max}$ (ml.kg^{-}1.min^{-1}) during a progressive incremental exercise test on a treadmill until exhaustion [42]

TTE during a progressive incremental exercise test on a treadmill (min) [42]

v$\dot{V}O_{2max}$ (km.h) during an incremental maximal test to exhaustion performed on a treadmill [43]

Peak treadmill velocity (km.h) during an incremental maximal test to exhaustion [43]

Anaerobic capacity (W) from a Wingate Test [44, 45, 46]

Peak power (W) from a Wingate Test [44, 45, 46]

Power decline (W) from a Wingate Test [44]

Margaria-Kalamen (kgm.s) [44]

Cycled for 2 hours at 70% $\dot{V}O_{2peak}$ and then completed a 4 kJ/kg body weight TT on a cycle ergometer (min) [47]

Power output (W) during a continuously graded incremental test until exhaustion on a cycle ergometer [48]

TTE (min) during a continuously graded incremental test until exhaustion on a cycle ergometer [48]

$\dot{V}O_{2peak}$ (l.min) from a continuously graded incremental test until exhaustion on a cycle ergometer [48]

$\dot{V}O_{2max}$ (ml.kg-1.min-1) from an incremental graded-exercise test until volitional exhaustion on a cycle ergometer [49]

TTE (min) from an incremental graded-exercise test until volitional exhaustion on a cycle ergometer [49]

$\dot{V}O_{2max}$ ($l.min^{-1}$) from a progressively increasing protocol for nine minutes on a cycle ergometer [50]

Working capacity at a heart rate of 170 b.min (W) from a progressively increasing protocol for nine minutes on a cycle ergometer [50]

Maximal pedalling time (s) from a progressively increasing protocol for nine minutes on a cycle ergometer [50]

$\dot{V}O_{2max}$ (ml.kg-1.min-1) from a maximal incremental exercise treadmill protocol until exhaustion [51]

TTE (min) from a maximal incremental exercise treadmill protocol until exhaustion [51]

$\dot{V}O_{2max}$ (ml.kg-1.min-1) from an incremental test on a cycle ergometer until exhaustion [52, 53, 54]

TTE (s) during a progressive maximal exercise test performed on a cycle ergometer [54]

$\dot{V}O_{2max}$ (ml.kg-1.min-1) [55]

TTE during a 1.5-mile run-walk (s) [55]

TTE during a 600-yard run-walk (s) [55]

Distance covered during a 12-minute run-walk (miles) [55]

$\dot{V}O_{2max}$ (ml.kg-1.min-1) during a graded exercise test on a cycle ergometer until exhaustion [56]

Maximal cycling power (W) during a force-velocity test [20]

Optimal velocity (rpm) during a force-velocity test [20]

Optimal force (kg) during a force-velocity test [20]

Physical working capacity (kg.m.min) [57]

$\dot{V}O_{2max}$ ($l.min^{-1}$) from an incremental stress test until exhaustion on a cycle ergometer [58, 59, 60]

TTE (s) from an incremental stress test until exhaustion on a cycle ergometer [58, 59, 60]

Maximum power output (W) from an incremental stress test until exhaustion on a cycle ergometer [58, 59]

$\dot{V}O_{2max}$ (ml.kg-1.min-1) from a maximal progressive incremental test until exhaustion on a cycle ergometer [61, 62]

TTE (min) during a prolonged exercise performance test on a cycle ergometer at 60% $\dot{V}O_{2max}$ followed by an incremental exercise test until exhaustion [63]

Sprint time (s) at 5, 10 and 30 m [25]

Distance covered during Yo-Yo Intermittent Endurance Test (m) [25, 37]

Maximum power output (kpm.min) during a progressive incremental exercise test to exhaustion on a cycle ergometer [64]

Cycling TTE at 90% W_{max} (min) [64]

Peak power (W.kg), from a Wingate test [65]

Mean power (W.kg) from a Wingate test [65]

Fatigue index (%) from a Wingate test [45, 46, 65]

Peak cycling power (W.kg) during a ramp test on a cycle ergometer until exhaustion [66]

$\dot{V}O_{2max}$ ($l.min^{-1}$) from a continuous progressive test until exhaustion on a treadmill [27]

Anaerobic speed test (s) [27]

TTE during an endurance run at 90% $\dot{V}O_{2max}$ (s) [27]

TTE (s) during a 20 s repeat sprint continuous incremental protocol until exhaustion on a treadmill [67]

TTE (min) during a continuous incremental exercise protocol on a treadmill [68]

16 km TT performance (min) on a cycle ergometer [69]

15 km TT performance (min) on a cycle ergometer [70]

30 km TT performance (min) on a cycle ergometer [70]

Tennis serve performance accuracy [30]

Tennis serve performance velocity (mph) [30]

100-m freestyle time (s) [32]

200-m freestyle time (s) [32]

Peak power output (W) from an incremental exercise test on a cycle ergometer [60]

Total work done (kJ) from an incremental exercise test on a cycle ergometer [60]

Sprint duration until exhaustion throughout maximum accumulated oxygen deficit tests on a cycle ergometer [71]

Power relative (W.kg) from an incremental test until voluntary exhaustion on a cycle ergometer [72]

$\dot{V}O_{2max}$ (ml.min) from an incremental test until voluntary exhaustion on a cycle ergometer [72]

Distance ran during Loughborough Intermittent Shuttle Test (m) [73]

15 m sprint time (s) [73]

Mean and peak power outputs during an all-out 30 second sprint (W) [74]

TTE (min) from an incremental maximal exercise test on a cycle ergometer [75]

Repeated shuttle-sprint ability test mean time (s) [37]

Peak and mean power output during repeat sprint tests (W) [76]

Fatigue index for power during repeat sprint tests (%) [76]

Peak and mean speed during repeat sprint tests (m.s) [76]

Fatigue index for speed during repeat sprint tests (m.s) [76]

Incremental rowing ergometer test to determine $\dot{V}O_{2max}$ (l.min) [77]

Incremental rowing ergometer test to determine maximal power output (W) [77]

Time of attaining anaerobic peak power during maximal cycling sprint test (s) [78]

Time of maintaining anaerobic peak power during maximal cycling sprint test (s) [78]

Power decrease during maximal cycling sprint test (W.kg.s) [78]

Peak cycling power during an incremental test on a cycle ergometer until exhaustion (W.kg) [78]

TTE, time to exhaustion; MILS, maximal isometric lifting strength; $\dot{V}O_{2max}$ maximal oxygen uptake; $\dot{V}O_{2peak}$ peak oxygen uptake; $v\dot{V}O_{2max,}$ velocity at maximal oxygen uptake.

Please note that exact duplicate outcomes were deleted.

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Electronic Supplementary Material Appendix S3. Example of a Search Strategy Conducted in PubMed (14/01/2019).

Limits applied	
Humans	
Females	
English language	
Search terms	**Number of results**
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and athletic performance	221
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and sports performance	277
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and strength	197
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and torque	16
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and force	144
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and max* voluntary contraction	24
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and isometric	55
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and isokinetic	16
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and neuromuscular	46
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and skeletal muscle	184
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and muscular performance	14
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and power	285
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and anaerobic	65
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and anaerobic capacity	9
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and anaerobic power	12

Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and aerobic	119
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and endurance	158
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and aerobic capacity	27
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and aerobic power	19
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and endurance capacity	26
Menstrual cycle OR menstrual phase OR follicular phase OR luteal phase and endurance power	13
Total: 1927 (with duplicates)	

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Electronic Supplementary Material Appendix S4. Study Quality Assessment.

Downs and Black checklist (maximum score attainable = 16). Study quality was categorised as follows: "high": 14 – 16; "moderate": 10 – 13; "low": 6 – 9; "very low": 0 - 5).	
	Reporting
Q1.	Is the hypothesis/aim/objective of the study clearly described? Yes = 1 No = 0
Q2.	Are the main outcomes to be measured clearly described in the introduction or methods section? If the main outcomes are first mentioned in the results section, answer no. Yes = 1 No = 0
Q3.	Are the characteristics of the participants included in the study clearly described? In observational studies, inclusion and/or exclusion criteria should be given. In case-control studies, inclusion and/or exclusion and the source of controls should be given. Yes = 1 No = 0
Q4.	Were the tested menstrual cycle phases clearly described? Answer yes if the precise criteria used to define phase were provided, answer no if the exact phase tested cannot be ascertained (*e.g.,* vague language such as "early" or "late" were used, without defining the criteria) Yes = 1 No = 0
Q5.	Are the main findings of the study clearly described? Simple outcome data should be reported for all major findings so the reader can check the major analyses and conclusions. This does not cover statistical tests which are addressed in other questions. Yes = 1 No = 0
Q6.	Does the study provide estimates of the random variability in the data for the main outcomes? In non-normal data, inter-quartile range should be reported. In normal data, standard deviation, standard error or confidence intervals should be reported. Yes = 1 No = 0
	External validity
Q7.	Were the subjects confirmed as non-hormonal contraceptive users, for at least three months prior to participation?

	Yes = 1
	No = 0
	Unable to determine = 0
	Internal validity – bias
Q8.	Was at least one familiarization trial conducted prior to exercise testing?
	Yes = 1
	No = 0
	Unable to determine = 0
Q9.	Were the exercise test conditions adequately standardised (taking into consideration factors including time of day, prior nutritional intake [including caffeine] and prior exercise).
	Yes (all relevant factors standardised) = 2
	Yes (some relevant factors standardised) = 1
	Exercise testing unstandardized = 0
	Unable to determine = 0
Q.10	If any of the results of the study were based on 'data dredging' was this made clear? Any analyses that had not been planned at the outset should be clearly indicated. If no retrospective subgroup analyses were reported, then answer yes.
	Yes = 1
	No = 0
	Unable to determine = 0
Q11.	Were statistical tests used to assess the main outcomes appropriate? The statistical techniques used must be appropriate to the data and the research question.
	Yes = 1
	No = 0
	Unable to determine = 0
Q12.	Were the main outcome measures used accurate (*i.e.,* valid and reproducible)? For studies where the validity and reproducibility of outcome measures are clearly described, the question should be answered yes. For studies which refer to other work that demonstrates the outcome measures are accurate, answer yes.
	Yes = 1
	No = 0
	Unable to determine = 0
	Internal validity – confounding (selection bias)
Q.13	Was the order of phase testing randomised?
	Yes = 1
	No = 0
	Unable to determine = 0
	Power

Q.14	Did the study have sufficient power to detect an *a priori* specified scientifically important effect at a pre-determined probability threshold? Answer yes if they included a power calculation, and no if not. Yes = 1 No = 0
Q15.	Was study retention > 85%? Yes = 1 No = 0 Unable to determine = 0
GRADE (assign an *a-priori* study quality rating based on the modified Downs and Black checklist, so all studies will start out as being of "high", "moderate", "low", "very low").	
Q1.	Identify if menstrual cycle phase was confirmed using blood samples. If yes, the *a priori* rating is maintained and this is the final study quality rating. If not, the study is downgraded a level (*e.g.,* a study that started out as high, drops to moderate).
Q2.	Identify if menstrual cycle phase was confirmed using ovulation kits. If yes, the Q1. rating is maintained. If no the study is downgraded another level (*e.g.,* a study that started out high, drops to low). This means that the maximum rating that any study that does not use blood analysis or ovulation kits is "low" or "very low".

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Electronic Supplementary Material Appendix S5. Table of Included Studies.

Author and date	Aim	Population (participant health, training status and sample size)	MC phases tested	Methods of determining MC phase	Outcome measure(s)	Study conclusion	Quality rating
Abt *et al.* (2007) [1]	To determine whether MC phase affects fine motor coordination, postural stability, knee strength and knee joint kinematics and kinetics	Physically active females (n = 10)	EF, ovulation and ML	Counting of days, MC history, urinary ovulation detection test and serum oestrogen and progesterone	Hamstring:quadricep strength ratio at 60 and 180 s^{-1}	No differences existed between phases of the MC for hamstring:quadriceps strength ratio at 60 and 180 s^{-1}	Moderate
Ansdell *et al.* (2019) [2]	To investigate knee extensor neuromuscular function and fatigability across the MC	Eumenorrheic females (n = 13)	EF, ovulation and ML	Counting of days, MC history, and serum oestrogen and progesterone	MVC with motor nerve stimulation (N) Time to task failure during fatiguing task involving sets of intermittent isometric contractions (s) performed in the lower-body	MVC was not affected by MC phase. Time to task failure was longer in the ML phase compared to both the EF and ovulatory phases	Moderate

Bailey *et al.* (2000) [3]	To determine whether MC phase influences the effect of carbohydrate supplementation on substrate metabolism and fatigue during prolonged exercise	Moderately trained female cyclists (n = 9)	EF and ML	Counting of days and serum oestrogen and progesterone	Cycling TTE at 70% $\dot{V}O_{2peak}$ (min)	No differences in TTE were observed between MC phases	Low
Bambaeichi *et al.* (2004) [4]	To determine whether the isolated and combined effects of circamensal variation and diurnal changes affect muscle strength	Sedentary females (n = 8)	EF, LF, ovulation, ML and LL	Counting of days, MC history, BBT (one month prior) and urinary ovulation detection test	Peak isokinetic torques of the knee flexors and extensors at 1.05 and 3.14 rad.s^{-1} (Nm) through 90º range of motion Maximal voluntary isometric contraction of the knee flexors and extensors measured at (Nm) 0 rad.s^{-1} and 60º of knee flexion with and without electrical stimulation	MC phase variation was observed for peak torque of knee flexors at 1.05 and 3.14 rad.s (Nm) and also isometric contraction of knee flexors, with values being greatest at the ovulation phase	Low
Bandyopadhyay and Dalui (2012) [5]	To determine whether MC phase influences endurance capacity and cardiorespiratory responses	Sedentary females (n = 45)	EF, LF and ML	Counting of days and BBT	Queens College Step Test to predict $\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1}) Running TTE at a heart rate of 135–140 b.min^{-1} (min)	$\dot{V}O_{2max}$ and running TTE were lower in the EF phase	Very low

Beidleman *et al.* (1999) [6]	To determine whether MC phase affects maximal and submaximal exercise performance at sea level and acute altitude	Physically active females (n = 8)	EF and ML	MC history, counting of days, urinary ovulation detection test and serum oestrogen and progesterone	$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1} or l.min^{-1}) during a progressive-intensity, continuous, treadmill running test to exhaustion Running TTE at 70% $\dot{V}O_{2peak}$ (min)	Neither $\dot{V}O_{2max}$ nor running TTE was affected by MC phase	High
Bell *et al.* (2011) [7]	To determine whether MC phase affects hamstring neuro-mechanics and leg stiffness	Physically active females (n = 15)	EF and ovulation	Counting of days, MC history, urinary ovulation detection test and serum oestrogen and progesterone	Rate of force production during a maximal voluntary isometric hamstring contraction (N.s^{-1}) Time to 50% peak force during a maximal voluntary isometric hamstring contraction (ms)	No changes were observed across the MC for both variables	Moderate
Bemben *et al.* (1995) [8]	To determine whether MC phase affects ventilatory and blood lactate responses to maximal treadmill exercise	Moderately active women (n = 5)	EF, ovulation and ML	Coutning of days, BBT and serum oestrogen and progesterone	$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1}) and running TTE during a progressive incremental exercise test (min)	There were no differences in $\dot{V}O_{2max}$ and running TTE between MC phases	Low

[a]Birch and Reilly (1999) [9]	To determine whether MC phase affects the physical, physiological and subjective responses to both isometric and dynamic lifting performance	Healthy females (n = 17)	EF, LF, ovulation, ML and LL	Counting of days, MC history, BBT (two months prior and during), and assessment of symptoms and alterations in cervical mucus	MILS performed at both knee and waist height (N) Time to volitional fatigue at 45% MILS performed at both knee and waist height (s) Maximal acceptable load (kg)	No differences between MC phases were identified for any of the lifting performances variables	Very low
[b]Birch and Reilly (2002) [10]	To determine whether the circamensal and diurnal rhythms in temperature affect the production of maximal voluntary muscle force	Moderately physically active females (n = 10)	LF and ML	Counting of days, MC history, BBT and assessment of symptoms and alterations in cervical mucus	MILS at knee height (N) Time to volitional fatigue at 45% MILS at knee height (min)	MILS and time to fatigue did not differ between either MC phase	Very low
Burrows and Bird (2005) [11]	To determine whether MC phase affects $v\dot{V}O_{2max}$ and peak treadmill velocity in a homogenous group of highly trained female endurance runners	Highly trained endurance females (n = 10)	EF, LF, EL and LL	MC history, counting of days and salivary progesterone	$v\dot{V}O_{2max}$ (km.h) and peak treadmill velocity (km.h) during an incremental maximal test to exhaustion performed on a treadmill	No differences in $v\dot{V}O_{2max}$ or peak treadmill velocity were found between the phases of the MC	Low
Bushman *et al.* (2006) [12]	To determine whether MC phase affects short term, high intensity (power) performance in moderately active women	Active females (n = 7)	EF and EL	MC history, counting of days, BBT and urinary	Anaerobic capacity, peak power and power decline from a Wingate Test (W)	There were no differences in Wingate or Margaria-Kalamen	Low

				ovulation detection test	Margaria-Kalamen (kgm.s)	performance between MC phases	
Campbell *et al.* (2001) [13]	To determine whether MC phase and carbohydrate ingestion affects glucose kinetics and exercise performance	Healthy, moderately endurance-trained women (n = 8)	EF and ML	MC history, urinary ovulation detection test and serum oestrogen and progesterone	Cycled for 2 hrs at 70% $\dot{V}O_{2max}$ and then completed a 4 kJ/kg body weight TT performance on a cycle ergometer (min)	TT performance was longer in the EF phase, compared to the ML phase of the MC	Moderate
Casazza *et al.* (2002) [14]	To determine whether MC phase affects peak exercise capacity, as measured by $\dot{V}O_{2peak}$	Healthy, habitually exercised females (n = 6)	LF and ML	MC history, counting of days, urinary ovulation detection test and serum oestrogen and progesterone	Power output (W), TTE (min) and $\dot{V}O_{2peak}$ (l.min) from a continuously graded test on a cycle ergometer	MC phase does not affect peak exercise capacity, with no changes in power output, TTE and $\dot{V}O_{2peak}$	Moderate
Davis *et al.* (1991) [15]	To determine whether MC phase affects muscle performance	Healthy females (n = 12)	EF, ovulation and ML	No information	Handgrip strength (N) Standing long jump performance x body mass (kg.m)	Handgrip strength and performance was superior during the EF than both the ovulatory and ML phases of the MC. Standing long jump performance was again superior during the EF phase, although not with	Very low

						respect to the ML phase of the MC	
Dean *et al.* (2003) [16]	To determine whether MC phase affects lactate threshold	Habitually active females (n = 8)	EF, LF and ML	MC history, counting of days, BBT and serum oestrogen and progesterone	$\dot{V}O_{2max}$ and TTE (min) from an incremental graded-exercise test until volitional exhaustion on a cycle ergometer	There were no MC phase differences in $\dot{V}O_{2max}$ and TTE	Low
De Bruyn-Prevost *et al.* (1984) [17]	To determine whether MC phase affects the physiological response to aerobic and anaerobic tests by young women	Healthy females (n = 7)	EF, ovulation and LL	BBT	Progressively increasing protocol for nine minutes on a cycle ergometer to determine $\dot{V}O_{2max}$ ($l.min^{-1}$), working capacity (W) and maximal pedalling time (s)	There were no differences in any performance variables measures across the MC	Very low
De Souza *et al.* (1990) [18]	To determine whether MC phase affects the physiological and metabolic responses to maximal and submaximal exercise in eumenorrheic runners	Well-conditioned female athletes (n = 8)	EF and ML	MC history, counting of days, urinary ovulation detection test (one month prior, during and one month post) and serum oestrogen and progesterone	Maximal exercise treadmill protocol to determine $\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$) and TTE (min)	No differences were observed for $\dot{V}O_{2max}$ and TTE between MC phases	High

Dibrezzo *et al.* (1988) [19]	To determine whether MC phase affects dynamic strength and work performance of the knee flexors and extensors	Healthy females (n = 21)	EF, ovulation and LL	MC history, counting of days	Mean peak torque of knee flexors and extensors at 60, 180, 240º.s (Nm) Muscular endurance and work ratios of knee flexors and extensors	There were no differences in mean peak torque or work ratios among the three MC phases	Very low
Dombovy *et al.* (1987) [20]	To determine whether MC phase affects the ventilatory response and exercise performance in normally menstruating, non-athletic women	Females not currently in active physical training (n = 8)	LF and ML	MC history, counting of days and serum oestrogen and progesterone	Incremental test on a cycle ergometer to determine $\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)	There were no differences in $\dot{V}O_{2max}$ across the MC	Moderate
Doolittle and Engebretsen (1972) [21]	To determine whether MC phase affects variations in performance	Healthy females (n = 16)	LF, ovulation, EL and LL	Counting of days	$\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$) TTE during a 1.5-mile run-walk (s) TTE during a 600-yard run-walk (s) Distance covered during a 12-minute run-walk (miles)	There were no differences in any performance variable measured across the MC	Very low
Drake *et al.* (2003) [22]	To determine whether MC phase affects electromyography and mechanomyography during	Females not involved in any exercise program (n = 7)	EF, LF, ovulation and EL	MC history, counting of days, urinary ovulation detection test	Maximal torque during an isometric muscle action (Nm) Torque at a sub-maximal (20, 50, 75%)	There were no differences in maximal and sub-maximal torque	Low

	isometric muscle actions of the rectus femoris				isometric muscle action (Nm)	variables between MC phases	
Ekenros *et al.* (2013) [23]	To determine whether MC phase affects muscle strength in the upper and lower limb, as well as hop performance	Females involved in recreational physical activity (n = 9)	EF, ovulation and ML	Counting of days, urinary ovulation detection test and serum oestrogen and progesterone	Peak isokinetic muscle torque of knee extensors at 120º.s (Nm) Handgrip strength (kg) Peak length of hop during a one-leg hop test (cm)	No differences in handgrip strength and hop performance were reported between MC phases. Peak torque of knee extensors changed across the MC whereby performance was greater in the ML phase compared to the EF phase	Moderate
[a]Elliott *et al.* (2003) [24]	To determine whether MC phase affects maximum force production in young women	Sedentary females (n = 7)	EF and ML	MC history, counting of days, urinary ovulation detection test and serum oestrogen and progesterone	Maximum voluntary isometric force of the first dorsal interosseous (N)	There were no differences in muscle strength between the EF and ML phases of the MC	Moderate
[b]Elliott *et al.* (2005) [25]	To determine whether MC phase affects muscle strength and sex hormone bioavailability	Healthy females (n = 7)	EF and ML	MC history, counting of days, urinary ovulation detection test and serum oestrogen and progesterone	Maximum voluntary isometric force of the first dorsal interosseous (N)	There were no differences in muscle strength during the MC	High

Ettinger *et al.* (1998) [26]	To determine whether MC phase affects reflex responses to static handgrip at 30% maximal voluntary contraction in women	Healthy females (n = 10)	EF and LF	Serum oestrogen and progesterone	Handgrip strength (kg)	There were no differences in handgrip MVC strength between MC phases	Low
Frandsen *et al.* (2020) [27]	To determine the influence of the MC on whole body peak fat oxidation rate during a graded exercise test	Recreationally active females (n = 19)	LF, ovulation and ML	MC history and serum oestrogen and progesterone	$\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$) during a graded exercise test on a cycle ergometer until exhaustion	There were no differences in $\dot{V}O_{2max}$ between MC phases	Low
Friden *et al.* (2003) [28]	To determine whether MC phase affects muscle strength and muscle endurance	Physically active females (n = 10)	EF, ovulation and ML	Counting of days, urinary ovulation detection test and serum oestrogen and progesterone	Peak handgrip strength (kg) Best jump during a one-leg hop test (cm) Maximal isokinetic muscle torque at 120º.s (Nm)	No variation in any performance variable was detected during the different phases of the MC	Low
Giacomoni *et al.* (2000) [29]	To determine whether MC phase affects maximal anaerobic performance during short-term anaerobic tests	Healthy females (n = 7)	EF, LF and ML	MC history, counting of days and serum progesterone	Maximal cycling power (W), optimal velocity (rpm) and optimal force (kg) during a force-velocity test Maximal jump power during a multi-jump test (W.kg)	No differences were observed in the force-velocity test or jump test performance among the three phases of the MC	Moderate

					Maximal jump height from a squat jump test (cm)		
Girija and Veeraiah (2011) [30]	To determine whether MC phase affects physical working capacity in an Indian population	Healthy females (n = 40)	EF, LF and ML	Counting of days, serial follicular scanning	PWC (kg.m.min) performed on a cycle ergometer	PWC performance decreased in the ML and EF phases of the MC when compared to the LF phase	Very low
[a]Gordon *et al.* (2012) [31]	To determine the effects of MC phase on the development of peak torque across a range of isokinetic speeds	Well trained female participants (n = 11)	EF, LF, ML and LL	MC history, counting of days, salivary oestrogen and progesterone	Torque production (Nm) of the knee extensors and flexors at 60, 80, 120 and 240º.s	There are fluctuations in peak torque of the knee extensors in response to phases of the MC	Very low
[b]Gordon *et al.* (2017) [32]	To determine whether MC phase affects maximal oxygen uptake and associated cardio dynamic response	Physically active females (n = 10)	EF, LF, ML and LL	MC history, counting of days and salivary oestrogen and progesterone	Incremental stress test on a cycle ergometer to determine $\dot{V}O_{2max}$ ($l.min^{-1}$), TTE (s) and maximum power output (W)	There were no differences in $\dot{V}O_{2max}$, TTE and maximum power output across the MC phases	Very low
[a]Grucza *et al.* (1993) [33]	To determine whether MC phase affects changes in the thermo-sensitivity of the thermoregulatory system in exercising women	Physically active females (n = 10)	LF and ML	MC history and BBT (one month prior and during)	A maximal test on a cycle ergometer to determine $\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)	$\dot{V}O_{2max}$ did not differ between the phases of the MC	Very low

[b]Grucza *et al.* (2002) [34]	To determine whether MC phase affects cardiorespiratory responses to exercise	Physically active females (n = 10)	LF and ML	MC history and BBT (one month prior and during)	A maximal test on a cycle ergometer to determine $\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)	$\dot{V}O_{2max}$ was greater in the LF phase compared with the ML phase of the MC	Very low
Gur (1997) [35]	To determine whether MC phase affects reliability of concentric and eccentric isokinetic measurements and reciprocal moment ratios in knee muscles	Sedentary women (n = 16)	EF, LF and ML	MC history, counting of days and serum oestrogen and progesterone	Torque ratios (peak and total) during concentric and eccentric hamstring and quadriceps testing at 60 and 180º.s	Concentric and eccentric peak torques, and total works, and their reciprocal ratio was not different among the MC phases	Low
Hertel *et al.* (2006) [36]	To determine whether MC phase affects hamstring and quadriceps strength, knee joint position sense, postural control and knee joint laxity	Competitive soccer or stunt cheerleading female athletes (n = 14)	LF, ovulation and ML.	MC history, counting of days, urinary ovulation detection test (one month prior) and urinary oestrogen and progesterone	Peak torque of quadricep and hamstring flexors and extensors at 120º.s (Nm) Hamstring:quadricep strength ratio	There were no differences in the measures of strength (peak torque of hamstrings and hamstring:quadricep ratio) across the MC	Low
Hoeger-Bement *et al.* (2009) [37]	To determine whether MC phase affects exercise-induced analgesia in young women after a fatiguing isometric contraction	Healthy females (n = 20)	LF and ML	MC history, counting of days and urinary ovulation detection test	Time to task failure during a sustained isometric fatiguing contraction at 25% of MVC (s) performed in the upper-body	There was no difference in time to task failure of the sustained 25% MVC between the phases of the MC	Low

Hoshi (1997) [38]	To determine whether MC phase affects muscular strength, grip strength and back lift strength	Healthy females (n = 14)	EF, LF, ovulation and ML	Counting of days and serum oestrogen and progesterone	Handgrip strength (kg) Back lift strength (kg)	Handgrip strength was lower in the EF phase compared with all other MC phases. Back lift strength was lower in the EF phase compared with all other MC phases and was higher in the LF compared with ovulation and the ML phases of the MC	Low
[a]Janse de Jonge *et al.* (2001) [39]	To determine whether MC phase affects skeletal muscle strength, fatigue and contractile properties	Healthy females (n = 15)	EF, LF and ML	Counting of days, BBT, assessment of symptoms and serum oestrogen and progesterone	Isometric quadricep strength (N) with electrical stimulation Isokinetic strength of the quadricep flexors and extensors at 60°.s^{-1} (Nm) Handgrip strength (N)	No changes were found in any of the muscle function parameters throughout the MC	Low
[b]Janse de Jonge *et al.* (2012) [40]	To determine whether MC phase affects prolonged exercise performance in both temperate and hot, humid conditions	Recreationally active females (n = 8)	EF and ML	Counting of days, BBT and serum oestrogen and progesterone	TTE (min) during a prolonged exercise performance test on a cycle ergometer at 60% $\dot{V}O_{2max}$ followed by an	In temperate conditions, no changes in prolonged exercise performance were found over the MC	Moderate

					incremental exercise test until exhaustion		
Jarvis *et al.* (2011) [41]	To determine whether MC phase affects the cardiovascular and vasomotor sympathetic response during static handgrip to fatigue and post exercise circulatory arrest	Healthy females (n = 11)	EF and ML	Counting of days, urinary ovulation detection test and serum oestrogen and progesterone	Handgrip strength (kg) Time to fatigue during static handgrip at 40% of MVC (s)	MC phase did not influence MVC or time to fatigue	Moderate
Julian *et al.* (2017) [42]	To determine whether MC phase affects performance in soccer specific tests	High-level female soccer players (n = 9)	EF and ML	MC history, counting of days and serum oestrogen and progesterone	Sprint time (s) at 5, 10 and 30 m CMJ height (cm) Distance covered during Yo-Yo IET (m)	Yo-Yo IET performance was considerably lower during the ML phase as compared to the EF phase of the MC. There were no differences across the MC in all other performance variables	Low
Jurkowski *et al.* (1981) [43]	To determine whether MC phase affects exercise performance and the responses of oxygen transport, cardiac output and lactate production at several work rates	Healthy females (n = 9)	LF and ML	Counting of days, BBT and serum progesterone	Maximum power output (kpm.min) during a progressive incremental exercise test to exhaustion on a cycle ergometer	There was no difference in maximum power output across the MC. TTE was greater during the ML phase	Low

					Cycling TTE at 90% W_{max} (minutes)	compared to the LF phase of the MC	
Kaygisiz *et al.* (2003) [44]	To determine whether MC phase affects cardiorespiratory responses to exercise	Untrained females (n = 9)	LF and ML	MC history, counting of days and serum oestrogen and progesterone	Exercise test to exhaustion on a cycle ergometer determine $\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)	MC phase did not affect $\dot{V}O_{2max}$	Low
Kraemer *et al.* (2006) [45]	To determine whether MC phase affects plasma proenkephalin peptide F responses to high intensity exercise in young untrained eumenorrheic women	Active females not participating in a regular training program (n = 8)	EF and ML	MC history, BBT and serum oestrogen and progesterone	TTE (s) during a progressive maximal exercise test performed on a cycle ergometer	There were no differences in exercise duration between follicular and luteal phases	Low
Kubo *et al.* (2009) [46]	To determine whether MC phase affects changes in the mechanical properties of human muscle and tendon during the MC in vivo	Sedentary, or mildly to moderately active women (n = 8)	EF, ovulation and ML	MC history, BBT (two months prior and during) and serum oestrogen and progesterone	Maximal voluntary isometric strength of knee extensors and plantar flexors (Nm) with electrical stimulation	No change in muscle strength was found during the MC	Moderate
[a]Lara *et al.* (2019) [47]	To determine the effects of caffeine intake on Wingate anaerobic test performance during three phases of the MC	Female triathletes (n = 13)	EF, ovulation and ML	MC history, BBT and urinary ovulation detection test	Peak power (W.kg), mean power (W.kg) and fatigue index (%) from a Wingate Test	There was no difference in Wingate test performance between MC phases	Low

[b]Lara *et al.* (2019) [48]	To determine the ergogenic effects of caffeine in three phases of the MC	Female triathletes (n = 13)	EF, ovulation and ML	MC history, BBT and urinary ovulation detection test	Peak cycling power (W.kg) during a ramp test on a cycle ergometer until exhaustion	There was no difference in peak cycling power between MC phases	Low
Lebrun *et al.* (1995) [49]	To determine whether MC phase affects four selected induces of athletic performance: aerobic capacity, anaerobic capacity, isokinetic strength and high intensity endurance	Trained female athletes (n = 16)	EF and ML	MC history, ovulatory and menstrual symptoms, BBT and serum oestrogen and progesterone	$\dot{V}O_{2max}$ (l.min) from a continuous progressive test until exhaustion on a treadmill Anaerobic speed test (s) TTE during an endurance run at 90% $\dot{V}O_{2max}$ (s) Quadriceps and hamstring strength at 30º.s (Nm)	A higher $\dot{V}O_{2max}$ was reported in the EF phase compared to the ML phase. Anaerobic speed test, TTE and muscle strength was not influenced by MC phase	Low
Lee *et al.* (2014) [50]	To determine whether MC phase affects anterior cruciate ligament elasticity, force to flex the knee, and knee flexion–extension	Nonathletic females (n = 10)	EF, LF, ovulation and ML	MC history, counting of days and serum oestrogen and progesterone	Force to flex the knee from 90 to 125° (N)	Force to flex the knee was less at ovulation compared to the EF phase of the MC	Low
Lynch and Nimmo (1998) [51]	To determine whether MC phase affects intermittent exercise performance and	Recreationally active females (n = 10)	LF and LL	MC history, counting of days and serum progesterone	TTE (s) during a 20 s repeat sprint continuous incremental protocol on a treadmill	There was no difference in performance between	Moderate

	some commonly used metabolic markers					the LF and the LL phases of the MC	
Materson (1999) [52]	To determine whether MC phase affects anaerobic power performance	Fairly active females (n = 32)	EF and ML	MC history and counting of days	Anaerobic capacity (W), anaerobic power (W) and fatigue index (%) from a Wingate Test	Wingate performance improved in the ML phase compared with the EF phase of the MC	Very low
Mattu *et al.* (2019) [53]	To determine whether MC phase affects submaximal and maximal responses to exercise	Active females (n = 15)	LF and ML	MC history and urinary ovulation detection test	TTE on a cycle ergometer (s) $\dot{V}O_{2max}$ (l.min) and peak power output (W) from an incremental exercise test on a cycle ergometer	MC phase did not affect the submaximal and maximal exercise responses	Low
McCracken *et al.* (1994) [54]	To determine whether MC phase affects the blood lactate levels in response to intensive running	Physically active females (n = 9)	LF and ML	MC history, BBT (two months prior) and urinary oestrogen and progesterone	TTE (min) during an incremental and continuous exercise protocol on a treadmill	Running TTE was not different between the LF and ML phases of the MC	Low
McLay *et al.* (2007) [55]	To determine whether MC phase affects muscle-glycogen storage, exercise performance, and substrate metabolism at varying exercise intensities	Moderately trained women (n = 8)	LF and LL	BBT and serum oestrogen and progesterone	16 km TT performance (min) on a cycle ergometer	TT performance was not affected by MC phase	Moderate

Montgomery and Shultz (2010) [56]	To determine whether MC phase affects maximal voluntary isometric contraction torque of the knee flexors and extensors	Recreationally active females (n = 29)	EF and EL	MC history, urinary ovulation detection kit and serum oestrogen and progesterone	Maximal voluntary isometric strength of the quadriceps and hamstrings (Nm.kg)	There was no difference in muscle strength between MC phases	Moderate
Okudan *et al.* (2005) [57]	To determine whether MC phase affects anaerobic performance	Sedentary females (n = 15)	LF, ovulation and ML	Serum oestrogen and progesterone	Anaerobic capacity (W), anaerobic power (W) and fatigue index (%) from a Wingate Test	There was no difference between the peak power, mean power and fatigue index calculated in three different phases of the MC	Low
Oosthuyse *et al.* (2005) [58]	To determine whether MC phase affects exercise performance by means of a cycling time trial	Trained (n = 5) and untrained (n = 8) female cyclists	EF, LF and ML	Counting of days, BBT, urinary ovulation detection test and serum oestrogen and progesterone	15 km TT performance (min) on a cycle ergometer 30 km TT performance (min) on a cycle ergometer	There was no difference in TT performance between MC phases in either the trained and untrained groups. Analysis of the combined trained and untrained group data revealed a trend for a faster TT time in the LF phase compared	High

						to the EF phase of the MC	
Otaka *et al.* (2018) [59]	To determine whether MC phase affects tennis performance with and without dehydroepiandrosterone sulphate supplementation	Division 1 collegiate female tennis players (n = 10)	EF, LF, ovulation and ML	Counting of days	Isometric hip strength (Nm) Tennis serve performance accuracy Tennis serve performance velocity (mph)	The lowest tennis serve performance score (attributed to a change in accuracy and not velocity) occurred at ovulation. Isometric hip strength decreased at ovulation	Very low
Pallavi *et al.* (2017) [60]	To determine whether MC phase affects muscle strength variations and also the rate of fatigue	Untrained or moderately trained female students (n = 100)	EF, LF and ML	MC history	Work done (J) during Mosso's Ergograph test Handgrip strength (kg)	The amount of work done and handgrip strength was higher in the LF phase and reduced in the EF and ML phases of the MC	Very low
Petrofsky *et al.* (2007) [61]	To determine whether MC phase affects isometric endurance and skin and muscle blood flow during isometric exercise for contractions at low, medium and high isometric tensions	Females not engaged in athletic programs (n = 8)	EF, LF, ovulation, EL, ML and LL	MC history	Endurance time at 20, 40 and 60% handgrip MVC (s)	There was small variation in endurance time across the MC for contractions at 60% handgrip MVC. This effect increased at 40% and was greatest	Very low

						at 20% handgrip MVC	
Quadagno *et al.* (1991) [62]	To determine whether MC phase affects athletic performance as measured by weight lifting and swimming	Recreational female weight lifters (n = 12) and highly trained female swimmers (n = 15)	EF, LF and LL	MC history and counting of days	Bench and leg press mean weight lifted (pounds) 100-m freestyle swim time (s) 200-m freestyle swim time (s)	There were no differences in strength and swimming performance during the three MC phases	Very low
Redman *et al.* (2003) [63]	To determine whether MC phase affects the metabolic response to exercise	Sedentary females (n = 14)	LF and.ML	MC history, counting of days, urinary ovulation detection test and serum oestrogen and progesterone	Peak power output (W), TTE (min), total work done (kJ) and $\dot{V}O_{2max}$ (l.min) from an incremental exercise test on a cycle ergometer	Incremental exercise test performance ($\dot{V}O_{2max}$), TTE, maximal power output and total work done were not different between the two MC phases	High
Rodrigues *et al.* (2019) [64]	To determine whether MC affects MVC of lower limbs	Recreationally trained females (n = 12)	LL, EF and LF	Counting of days	MVC (kg) during leg press exercise	MVC was greater in the EF phase than the LL phase. MVC was greater in the LF phase then both the EF and LL phases.	Low
Romero-Moraleda *et al.* (2019) [65]	To determine whether MC phase affects muscle	Female triathletes (n = 13)	EF, ovulation and ML	MC history, BBT and urinary	Mean and peak force at 20, 40, 60 and	Power outputs were very similar in all MC phases	Moderate

	performance during half-squat exercise			ovulation detection test	80% of one-repetition maximum performed on a Smith Machine		
Sarwar *et al.* (1996) [66]	To determine whether MC phase affects skeletal muscle strength, contractile properties and fatiguability in young, healthy females	Relatively sedentary (n = 10)	EF, LF, ovulation, ML and LL	Counting of days	Maximum voluntary isometric strength of the quadriceps (N) Handgrip strength (N)	There was an increase in quadriceps and handgrip strength at ovulation compared with other MC phases	Very low
Shaharudin *et al.* (2011) [67]	To determine whether MC phase affects anaerobic capacity in repeated sprint cycling bouts	Moderately physically active females (n = 12)	LF and ML	BBT (three months prior and during), MC history and serum progesterone	Sprint duration until exhaustion throughout maximum accumulated oxygen deficit tests on a cycle ergometer	There were no differences between MC phases in sprint duration until exhaustion throughout maximum accumulated oxygen deficit tests	Low
Sipaviciene *et al.* (2013) [68]	To determine whether MC phase affects susceptibility to exercise-induced muscle damage after stretch-shortening cycle exercise	Physically active women (n = 18)	EF and ovulation	BBT and serum oestrogen and progesterone	Jump height (cm) from a drop jump Maximum isometric torque of knee extensor muscles (Nm) with electrical stimulation	Jump height and MVC did not differ between MC phases	Low
Smekal *et al.* (2007) [69]	To determine whether MC phase affects the metabolic	Active females (n = 19)	LF and LL	MC history, BBT and serum oestrogen	Power relative (W.kg) and $\dot{V}O_{2max}$ (ml.min) from an incremental	There were no differences in power	Low

	and cardiorespiratory responses to exercise				test until voluntary exhaustion on a cycle ergometer	relative and $\dot{V}O_{2max}$ across the MC	
[a]Sunderland and Nevill (2003) [70]	To determine whether MC phase affects performance of high intensity intermittent running in the heat	Well trained female game players (n = 7)	LF and ML	Counting of days and serum oestrogen and progesterone	Distance ran during Loughborough Intermittent Shuttle Test (m) 15 m sprint time (s)	There were no differences in distance run or 15 m sprint time between MC phases	Low
[b]Sunderland *et al.* (2011) [71]	To determine whether MC phase affects the growth hormone response to sprint exercise among normally menstruating women	Physically active females (n = 8)	LF and ML	Urinary ovulation detection test and serum oestrogen and progesterone	Mean and peak power outputs during an all-out 30 second sprint (W) on a treadmill	Mean and peak power outputs during an all-out 30 second sprint did not differ across the MC	Moderate
Takase *et al.* (2002) [72]	To determine whether MC phase affects induced modulations in the cardiorespiratory response to exercise with and without acute exposure to altitude	Moderately trained female athletes (n = 9)	LF and ML	MC history, BBT and serum oestrogen and progesterone	TTE (min) from an incremental maximal exercise test on a cycle ergometer	MC phase did not affect exercise TTE	Moderate
Tenan *et al.* (2016) [73]	To determine whether MC phase affects maximal isometric force and tremor during an endurance task	Recreationally active females (n = 9)	EF, LF, ovulation, ML and LL	MC history and BBT (one month prior)	MVC (Nm) Mean time to task failure (s) during an endurance task	MVC in the ML phase was lower than LF, ovulatory, and LL phases. There was no effect of MC phase	Very low

						on mean time to task failure	
Tounsi *et al.* (2018) [74]	To determine whether MC phase affects soccer-related physical performance	Tunisian high-level soccer players (n = 11)	EF, LF and ML	Counting of days and serum progesterone	Distance covered during Yo-Yo IET (m) Repeated shuttle-sprint ability test mean time (s) Absolute performance during five-jump test (m)	None of the measured variables were altered due to MC phase	Low
Tsampoukos *et al.* (2010) [75]	To determine whether MC phase affects sprinting, recovery from sprinting and metabolic responses to sprinting	Highly active females (n = 8)	EF, ovulation and ML	MC history, urinary ovulation detection test and serum oestrogen and progesterone	Peak and mean power output during repeat sprint tests (W) Fatigue index for power during repeat sprint tests (%) Peak and mean speed during repeat sprint tests (m.s) Fatigue index for speed during repeat sprint tests (m.s)	All performance variables were unaltered due to MC phase.	High
Vaiksaar *et al.* (2011) [76]	To determine whether MC phase affects endurance performance in trained rowers	Competitive female rowers (n = 8)	LF and ML	MC history, counting of days and serum	Incremental rowing ergometer test to determine $\dot{V}O_{2max}$	There were no differences in $\dot{V}O_{2max}$ and power output	Moderate

				oestrogen and progesterone	(l.min) and maximal power output (W)	between the two MC phases	
Wearing *et al.* (1972) [77]	To determine whether MC phase affects selected tests of physical fitness.	Female intercollegiate basketball or volleyball players	EF, LF, EL and LL	No information	Standing broad jump distance (inches) Maximum hip flexion and extension strength (pounds)	Both standing broad jump and strength performance was reduced in the EF phase greatest in the LL phase of the MC	Very low
Wiecek *et al.* (2016) [78]	To determine whether MC phase affects the values of starting speed and anaerobic endurance	Physically active females (n = 16)	LF and ML	Counting of days, BBT and serum oestrogen and progesterone	Peak and mean power (W), time of attaining anaerobic peak power (s), time of maintaining anaerobic peak power (s) and power decrease (W.kg.s) during a maximal cycling sprint test	There were no differences between MC phases in the measured performance variables	Low

BBT, basal body temperature; CMJ, counter-movement jump; EF, early follicular; EL, early luteal; IET, intermittent endurance test; LF, late follicular; LL, late luteal; MC, menstrual cycle; MILS, maximal isometric lifting strength; ML, mid-luteal; MVC, maximal voluntary contraction; PWC, physical working capacity; TTE, time to exhaustion; TT, time trial; $\dot{V}O_{2max,}$ maximal oxygen uptake; $\dot{V}O_{2peak,}$ peak oxygen uptake; $v\dot{V}O_{2max,}$ velocity at maximal oxygen uptake.

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