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**Variations in Strength-Related Measures During the Menstrual Cycle in Eumenorrhoeic  
Women: A Systematic Review and Meta-Analysis**

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Appendix: 1 (supplementary table)

# Variations in Strength-Related Measures During the Menstrual Cycle in Eumenorrhic Women: A Systematic Review and Meta-Analysis

## Abstract

*Objectives:* To systematically review the current body of research that has investigated changes in strength-related variables during different phases of the menstrual cycle in eumenorrhic women. *Design:* Systematic review and meta-analysis. *Method:* A literature search was conducted in Pubmed, SPORTDiscus and Web of Science using search terms related to the menstrual cycle and strength-related measures. Two reviewers reached consensus that 21 studies met the criteria for inclusion. Methodological rigor was assessed using the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies. Random effects meta-analyses were used to compare the early-follicular, ovulatory and mid-luteal phases for maximal voluntary contraction, isokinetic peak torque, and explosive strength. *Results:* The assessment of study quality showed that a high level of bias exists in specific areas of study design. Non-significant and small or trivial effect sizes ( $p \geq 0.26$ , Hedges  $g \leq 0.35$ ) were identified for all strength-related variables in each comparison between phases. 95% confidence intervals for each comparison suggested the uncertainty associated with each estimate extends to a small effect on strength performance with unclear direction ( $-0.42 \leq g \leq 0.48$ ). The heterogeneity for each comparison was also small ( $p \geq 0.83$ ,  $I^2 = 0\%$ ). *Conclusions:* Strength status appears to be minimally altered ( $g \leq 0.35$ ) by the fluctuations in ovarian sex hormones that occur during the menstrual cycle. This finding should be interpreted with caution due to the methodological shortcomings identified by the quality assessment.

**Key words:** period, menstruation, oestrogen, progesterone, power, athletes

## 1. Introduction

The menstrual cycle represents an important biological rhythm in females that serves to prepare the uterus for gestation. In eumenorrhic women, a menstrual cycle typically lasts 28 days, but can vary considerably<sup>1</sup>. It is well-established that over the course of a menstrual cycle, women are exposed to a constant and rapidly shifting profile of endogenous sex hormones. Aside from their principal roles in reproductive function and control of sexual characteristics, the main female ovarian hormones (oestrogen and progesterone) circulating in the blood, influence a multitude of different physiological systems. Fluctuations in these, and other sex hormones, can explain variations in physical performance and physiological responses to exercise over the course of a menstrual cycle<sup>2</sup>, which has important implications for scientific research and the optimization of exercise prescription in females. In particular, the effect that changes in female reproductive hormones exert in strength-related tasks has received considerable attention and is widely debated<sup>2-5</sup>.

The menstrual cycle is traditionally divided into two distinct phases (follicular and luteal), which are separated by ovulation. These two phases are defined by ovarian function and differentiated by varying concentrations of oestrogen and progesterone. The follicular phase begins on the first day of menses (days 1-5) and is characterized by low concentrations of both oestrogen and progesterone. Oestrogen gradually increases during the follicular phase and peaks ~1 day prior to ovulation (typically 12-14 days after menstruation onset), which is triggered by a surge in the luteinizing hormone (LH). The rise in oestrogen and LH is also accompanied by a sharp and brief increase in testosterone, which is a precursor for the biosynthesis of oestrogen, and is considered to be important for sexual function and desire in females<sup>6</sup>. Following the ovulatory period, the early-luteal phase is characterized by decreasing oestrogen levels and a gradual rise in progesterone. Through the mid-luteal phase, oestrogen displays a bi-phasic response, resulting in high levels of both hormones before a gradual decrease over the following 5-7 days. Although this pattern of hormonal physiology is broadly present in all eumenorrhic females, the concentration of hormones and timing of cycle events, displays large inter-individual variability<sup>7</sup>, making scientific investigation in this area complex and challenging. Therefore, although many studies have investigated the effects of menstrual cycle

phase on exercise performance, it is prudent to examine the internal validity of these studies to ensure that the conclusions generated are accurate.

Oestrogen is responsible for the regulation of a number of important anabolic processes<sup>8</sup> and can influence central nervous system function<sup>9</sup>. Dehydroepiandrosterone (DHEA), the precursor to oestrogen and testosterone that peaks prior to ovulation, produces a net excitatory effect via its action on several neurotransmitter receptors<sup>10</sup>. Specifically, oestrogen is known to bind to receptor sites that attenuate the release of  $\gamma$ -aminobutyric acid<sup>11</sup>, a neurotransmitter responsible for reducing neuronal excitability and muscle tone. Additionally, oestrogen promotes the activation of glutamate releasing neuron receptors that cause an excitatory response in the nervous system<sup>12</sup>. In contrast, progesterone is known to exert a net inhibitory effect on the nervous system via enhancement of  $\gamma$ -aminobutyric acid action<sup>13</sup>. Variations in testosterone level across the menstrual cycle also produce physiological effects that may alter strength-related performance. Although absolute testosterone is low in females compared to males, a surge in testosterone during the late-follicular phase may benefit performance during short-intense activity, via increases in motivational drive<sup>14</sup>, and enhanced calcium kinetics in the muscle cell<sup>15</sup>. It is also possible that the thermogenic action of progesterone, which causes an increase in core body and skin temperature during the luteal phase<sup>16</sup>, positively influences nerve conduction velocity<sup>17</sup> and antagonistic co-contraction<sup>18</sup>, and consequently may positively influence performance in explosive strength-related tasks. Based upon these theoretical mechanisms, it is conceivable that oestrogen has an inotropic effect on muscular strength-related capabilities.

Strength can be defined as the ability of an individual to apply force under a specified set of movement constraints<sup>19</sup>. Increases in strength are associated with improvements in important markers of metabolic health<sup>20</sup>, everyday tasks<sup>21</sup>, a lower risk of injury<sup>22</sup>, and enhanced athletic performance<sup>23</sup>. Strength training is also important in counteracting conditions associated with muscle weakness, such as sarcopenia, musculoskeletal disorders, and prolonged immobilization<sup>24</sup>. Strength training also provides beneficial changes to the risk factors associated with anterior-cruciate ligament injury, which has a high incidence in female athletes injury<sup>25</sup>.

Findings from studies examining the influence of female sex hormones on strength-related performance have previously been summarized in several non-systematic narrative reviews and book chapters<sup>1-4,26</sup>. However, these works typically address the effects of female reproductive hormones on athletic performance qualities more broadly and concluded that the effects on muscular strength are equivocal. Consequently, the aim of this study was to systematically review the current body of research that has investigated changes in strength-related variables during different phases of the menstrual cycle in eumenorrheic women, and to conduct a meta-analysis of the data.

## 2. Methods

The complete protocol for this study was registered with PROSPERO International prospective register of systematic reviews (registration number: CRD42019126598). The guidelines provided by the Cochrane Musculoskeletal Group<sup>27</sup> were used as the basis for this systematic review. Fig. 1 provides a visual overview of the review and study selection process.

An initial scoping search was carried out in PubMed PubReMiner using the terms ‘strength’ AND ‘menstrual cycle’. The terms selected for the search strategy were defined *a priori* and were supplemented using medical subject headings provided by the scoping exercise. The search was conducted on October 8<sup>th</sup> 2018 in Pubmed, SPORTDiscus and Web of Science using the following search terms: [“menstrual cycle” OR “menstrual phase” OR “luteal phase” OR “follicular phase”] AND [“strength” OR “power” OR “torque” OR “force” OR “neuromuscular” OR “max\* voluntary contraction” OR “isometric” OR “isokinetic” OR “muscular performance”] NOT [“postmenopausal”]. No restriction was placed upon date or language of publication.

Studies that met the following pre-defined criteria were included in the review:

- Participants were eumenorrheic females (operationally defined as regularly occurring menstrual cycles of between 21-35 days for >6 months)

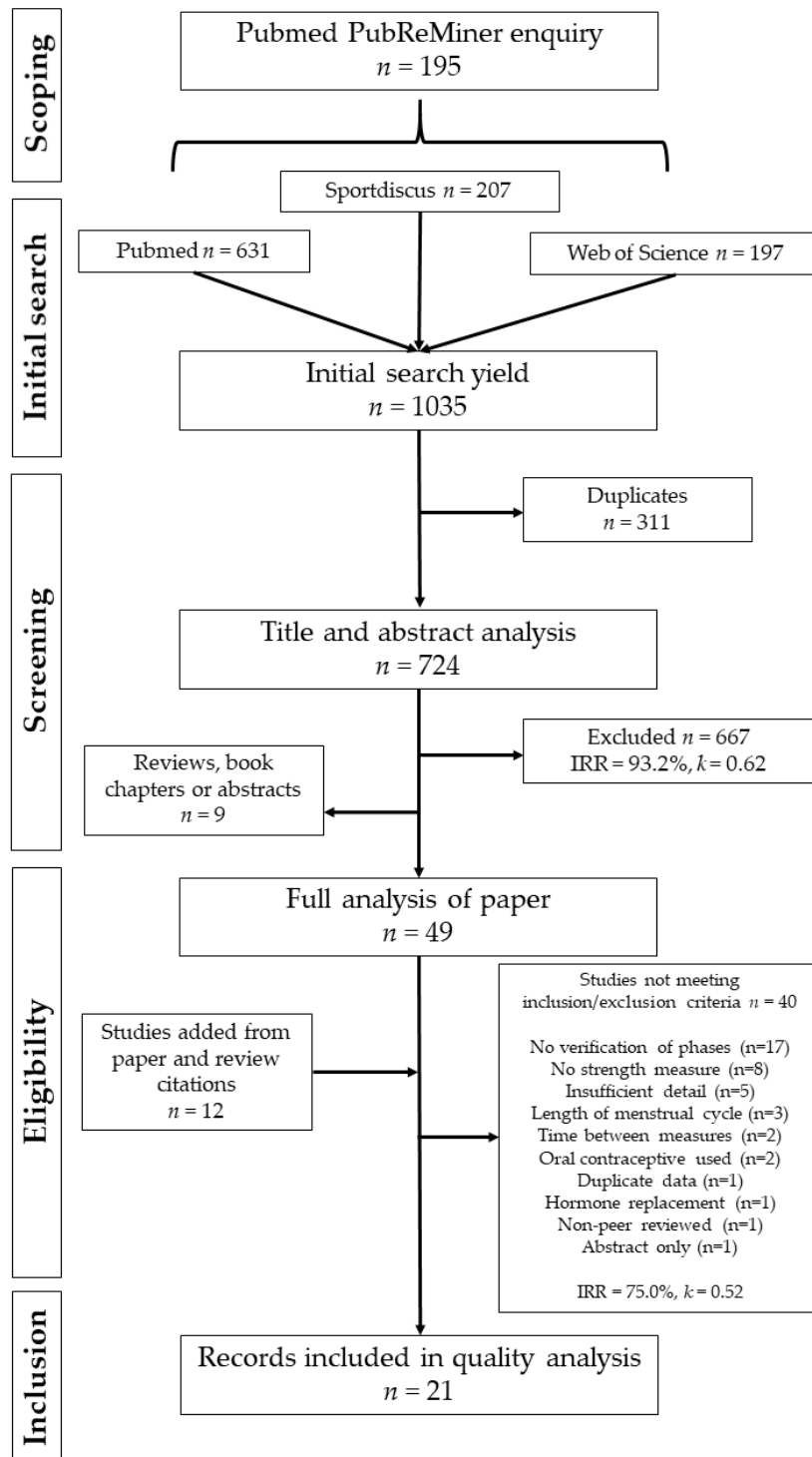
- At least one maximal muscular strength- or power-related outcome measure was taken
- Outcome measurements occurred in two or more defined phases (e.g. follicular, ovulatory, luteal) of the menstrual cycle
- A physiological measure of hormone levels or body temperature was taken to identify and/or verify menstrual cycle phases
- Published in full, in a peer-reviewed journal

The following exclusion criteria were also applied:

- Participants used one of the following forms of contraception: oral, implanted, injected, intrauterine devices, patches
- Participants received hormone replacement therapy
- Comparative time points were separated by longer than a regular menstrual cycle
- Participants suffered from an injury, illness or disease that may have affected performance in a test
- Description of measurement protocols and/or results were incomplete
- Ergogenic aids were used as part of the study

No limits were placed upon the training or competitive status of participants.





**Fig. 1** Search, screening and selection process for suitable studies. IRR = inter-rater reliability,  $k =$  Cohen's kappa statistic

The initial search returned 1035 papers, which were imported into a published software for systematic reviews<sup>28</sup>. Two reviewers (RB and GB) independently conducted each step of the study selection process (Fig. 1), with reasons for study exclusion noted by each reviewer. Any conflicts were resolved after each stage via discussion and consensus agreement between the reviewers. Following the removal of duplicate papers ( $n=311$ ), the title and abstract of each study were screened ( $n=724$ , inter-rater reliability (IRR): 93.2%, Cohens  $k=0.62$ ). Nine works were identified that were review articles, conference abstracts or book chapters, leaving 49 studies that were taken forward for full analysis. A further 12 papers were added following a process of citation checking of relevant systematic reviews and individual studies that appeared to meet the criteria for inclusion. These 61 papers were read in full by the two reviewers to assess suitability for inclusion (IRR: 75.0%, Cohens  $k=0.52$ ). This process resulted in the exclusion of a further 40 studies for the following reasons: no physiological verification of menstrual cycle phases ( $n=17$ ), no maximal strength-related measure ( $n=6$ ), results were not reported appropriately ( $n=4$ ), method provided insufficient detail ( $n=3$ ), menstrual cycle was longer than the pre-defined range or length unreported ( $n=3$ ), measurements were separated by  $>1$  menstrual cycle ( $n=2$ ), participants used oral contraceptive ( $n=2$ ), study was non-peer reviewed ( $n=1$ ) or not published in full ( $n=1$ ), duplicate data ( $n=1$ ), and participants received hormone replacement injections ( $n=1$ ).

Twenty-one studies were subsequently assessed for quality using the National Heart, Lung, and Blood Institute Quality Assessment Tool (NHLBI-QAT) for Observational Cohort and Cross-Sectional Studies. The tool comprises 14 items designed to assess the internal rigor of observational and cross-sectional research studies, with questions marked at 'yes' (low risk of bias), 'no' (high risk of bias) or 'other' (unclear risk of bias). A 15<sup>th</sup> item was added to identify whether the sequence of testing between menstrual cycle phases was randomized. This is important because, in the absence of sufficient familiarization to a strength-related task, a practice-effect may be present across trials, which may bias results. No studies were excluded based upon the results generated by the NHLBI-QAT and agreement between reviewers was high (IRR: 94.0%, Cohens  $k=0.87$ ).

The following data were extracted by the lead author (RB) and recorded in a spreadsheet: (1) author names, publication year and country of origin; (2) sample size and participant characteristics; (3) the timing of strength measurements during the menstrual cycle; (4) how menstrual cycle phase was identified and verified (5) how strength was assessed; and (6) the main findings regarding strength values at the time points used. Accuracy of data extraction was verified by a co-author (GB).

Review Manager (v5.3) was used to conduct random effect meta-analyses using the inverse variance method to compare the effect of menstrual cycle phases on strength-measures. The inverse-variance random effects model was selected because it weights trials proportionally based upon standard error values and heterogeneity across studies is also accounted for. The first day of menstruation was used as a common reference point to define menstrual cycle phases. Three comparisons were made: early-follicular phase ( $\leq 5$  days from menstruation onset) versus ovulatory phase ( $\pm 2$  days from ovulation), early-follicular phase versus mid-luteal phase ( $21 \pm 2$  days from menstruation onset or  $7 \pm 2$  days following ovulation), and ovulatory phase versus mid-luteal phase<sup>7</sup>. Values and comparisons between other time points in individual studies were also calculated for review purposes but were not entered into the meta-analysis due to the lack of data across studies at specific time points.

Outcome measures used in studies could be grouped into three categories based upon the strength quality assessed: maximal voluntary contraction (MVC), isokinetic peak torque (IPT, knee extension and knee flexion), and explosive strength (maximal jumping tasks, cycle ergometer peak power output, and rate of force development). A total of nine meta-analyses were therefore performed (three menstrual cycle phase comparisons for each of the three strength-related categories). Where studies reported an outcome measure more than once for different tasks, the data were pooled and entered as a single observation in order to avoid bias in the effect calculation caused by sampling dependence<sup>29</sup>.

Sample sizes and outcome measures with their respective standard deviation (SD) were inputted into the meta-analysis to calculate an effect size (ES) using Hedges *g* statistic with 95% confidence interval (CI). Values were interpreted as  $< 0.2$  (trivial);  $0.2-0.59$  (small);  $0.6-1.19$  (moderate); and  $\geq 1.2$

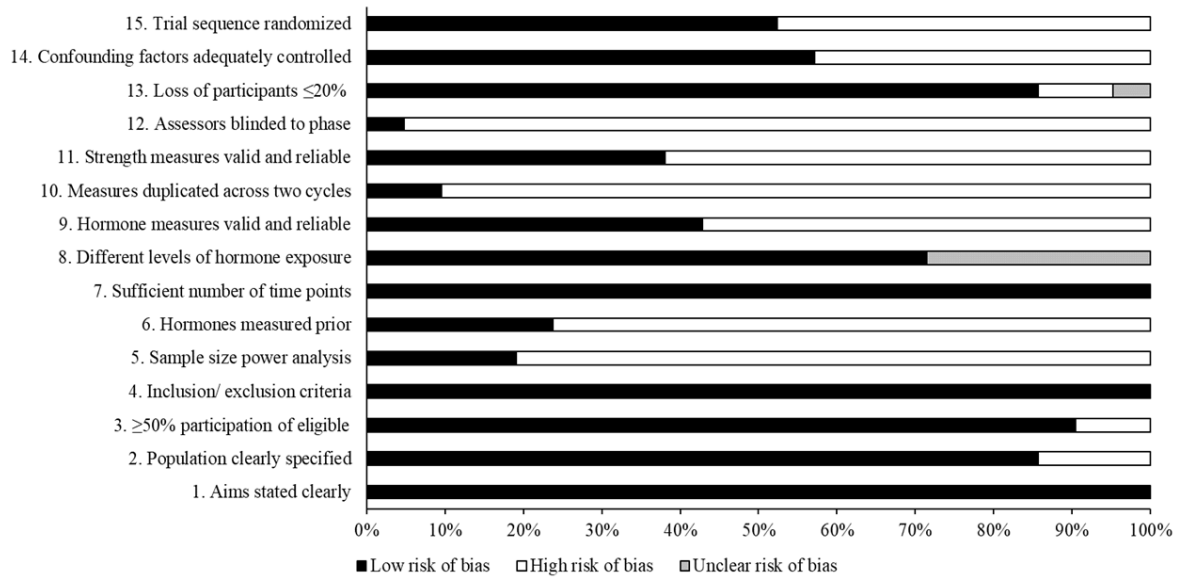
(large). The level of statistical heterogeneity between studies was quantified using the  $I^2$  statistic and corresponding  $p$ -value. Results are displayed as mean  $\pm$  SD, unless stated.

### 3. Results

The supplementary table provides a summary of the 21 studies that met the inclusion criteria. A total of 232 participants were included (mean age range: 19-30 years). Four studies used sedentary participants<sup>30-33</sup>, six studies used recreational or active participants<sup>34-39</sup>, five studies used moderately-trained participants<sup>40-44</sup>, three investigations used well-trained or Collegiate athletes<sup>45-47</sup>, and two studies used highly-trained or elite performers<sup>41,48</sup>. Two studies did not mention the training status of their participants<sup>49,50</sup>.

Fig. 2 provides an overview of the results from the NHLBI-QAT scores to highlight which features of study design present the highest risk of bias. Scores for studies ranged from 6 to 13 points out of total of 15 points (see supplementary table), with a mean score of  $8.8 \pm 1.9$  points. The physiological method used to identify and verify menstrual cycle phases varied considerably. Fifteen studies attempted to identify menstrual cycle phases/events prior to data collection using an estimate of basal body temperature<sup>30,32,36,38,39,43,49,50</sup> and/or LH concentration in the urine<sup>30-32,34,35,37,42,46</sup>, with the other six studies using only self-report strategies<sup>33,41,44,45,47,48</sup>. Twelve investigations measured oestrogen and progesterone concentrations prior to each trial in the blood<sup>32-35,37,38,42,43,47,50</sup>, saliva<sup>45</sup> or urine<sup>46</sup>, and a further three studies measured only progesterone in the blood<sup>36,44,48</sup>. One study assessed only salivary testosterone concentrations<sup>41</sup>, and five investigations did not verify differences between measurement time points with hormone measurements<sup>30,31,39,40,49</sup>. The validity and reliability of both the independent variables (hormones, item #9) and the dependent variables (strength measures, item #11) were reported in less than half of the studies. One study used a single-blind design<sup>34</sup>, and all but two studies<sup>41,42</sup> collected data over the course of a single menstrual cycle. Many studies had a low number of participants (mean:  $n=11$ ) and only four provided a sample size power analysis<sup>32,34,35,43</sup>. Eleven of

the 21 included studies conducted trials in a random order<sup>32,33,49,36,38–41,43–45</sup>, and ten studies were deemed to have adequately controlled for confounding variables<sup>30,32,36,39–41,43,44,47,48</sup>.



**Fig. 2** Summary of assessment of quality results using the National Heart, Lung, and Blood Institute Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies, to highlight areas where a high risk of bias exists.

The results of the random-effects meta-analyses are summarized in Table 1. Heterogeneity for each variable and sub-group was very small ( $p \geq 0.83$ ,  $I^2 = 0\%$ ). A MVC task was used in eleven studies<sup>30,31,50,32,35,37–40,42,49</sup> and all were entered in the meta-analysis ( $n=98$ ). Results showed non-significant and trivial differences ( $p \geq 0.93$ ,  $ES \leq 0.01$ ) in each of the three comparisons, with the uncertainty around effect size estimates extending to a small effect without clear direction (supplementary table). Three investigations observed significantly higher ( $p < 0.05$ ) MVC measures around ovulation compared to other menstrual cycle phases<sup>30,37,39</sup>.

Isokinetic peak torque was assessed in seven studies<sup>30,35,42,43,45,46,50</sup> ( $n=139$ ), with all but one<sup>43</sup> eligible for various meta-analytical comparisons between phases. Every study used knee extension dynamometry at angular velocities of 30 °.sec<sup>-1</sup><sup>43</sup>, 60 °.sec<sup>-1</sup><sup>30,45,50</sup>, 120 °.sec<sup>-1</sup><sup>35,42,45,46</sup>, 180 °.sec<sup>-1</sup><sup>30,45</sup> and 240 °.sec<sup>-1</sup><sup>45,50</sup>. Five of the seven studies also evaluated IPT in the knee flexors at the same angular velocities used to assess the knee extensors<sup>30,43,45,46,50</sup>. Taken together, results show that differences between menstrual cycle phases were non-significant and trivial for measures of IPT ( $p \geq 0.26$ ,  $ES \leq 0.08$ ). Sub-category analysis for IPT in the knee flexors revealed small differences between the early-follicular and ovulatory phases in favour of the early-follicular phase ( $p=0.34$ ,  $ES=-0.35$ , 95% CI: -1.07 to 0.37,  $n=15$ ). Three of the seven studies<sup>30,35,45</sup> observed significantly lower ( $p < 0.05$ ) values around menses compared to other times of the cycle, and Bambaiechi et al.<sup>30</sup> noted significantly higher scores around ovulation compared to menses, mid-follicular and luteal phases. One paper<sup>42</sup> reported a difference that was close to the threshold of significance ( $p=0.06$ ) in favour of the luteal phase compared to menses. The magnitude of the differences observed in these studies was trivial or small ( $ES \leq 0.49$ ).

A test of explosive strength capability was utilized in ten studies ( $n=96$ ), with measures categorized as: a maximal vertical or horizontal jumping task<sup>35,36,42,47,48</sup>, peak power output on a cycle ergometer<sup>33,36,41,44</sup>, and single joint isometric rate of force development or time to peak force<sup>34,38</sup>. Only one study was not entered into the meta-analysis<sup>44</sup> as the time points used did not fall within the pre-determined phases identified for comparison. Trivial differences between phases were noted for each comparison (Table 1,  $p \geq 0.74$ ,  $ES \leq 0.06$ ). The uncertainty of this estimate, reflected in the 95% CI, shows no clear direction to the differences for any phase comparisons. All ten individual studies reported non-significant differences ( $p > 0.05$ ) between time points with magnitudes considered trivial or small ( $ES \leq 0.44$ ).

1 **Table 1.** Results of random effects meta-analysis on differences between strength-related measures in menstrual cycle phases. Early-follicular phase ( $\leq 7$  days  
 2 from menstruation onset), ovulatory phase ( $\pm 2$  days from ovulation), mid-luteal phase ( $21 \pm 2$  days from menstruation onset or  $7 \pm 2$  days following ovulation).

3

Variables and sub- categories	Early-follicular vs ovulatory			Early-follicular vs mid-luteal			Ovulatory vs mid-luteal		
	<i>n</i>	Hedges <i>g</i> (95% CI)	<i>p</i> -value	<i>n</i>	Hedges <i>g</i> (95% CI)	<i>p</i> -value	<i>n</i>	Hedges <i>g</i> (95% CI)	<i>p</i> -value
<b>MVC</b>	<b>98</b>	<b>0.04 (-0.24 to 0.32)</b>	<b>0.80</b>	<b>98</b>	<b>-0.01 (-0.29 to 0.27)</b>	<b>0.93</b>	<b>82</b>	<b>0.01 (-0.30 to 0.31)</b>	<b>0.97</b>
<b>Isok peak torque</b>	<b>85</b>	<b>-0.17 (-0.47 to 0.14)</b>	<b>0.28</b>	<b>139</b>	<b>0.03 (-0.21 to 0.26)</b>	<b>0.82</b>	<b>85</b>	<b>0.04 (-0.26 to 0.34)</b>	<b>0.78</b>
Knee extension	56	-0.06 (-0.43 to 0.31)	0.76	83	0.03 (-0.27 to 0.34)	0.84	48	0.09 (-0.31 to 0.49)	0.66
Knee flexion	29	-0.38 (-0.90 to 0.14)	0.16	56	0.02 (-0.37 to 0.41)	0.92	37	-0.02 (-0.48 to 0.44)	0.94
<b>Explosive strength</b>	<b>79</b>	<b>0.09 (-0.22 to 0.40)</b>	<b>0.58</b>	<b>90</b>	<b>0.02 (-0.28 to 0.31)</b>	<b>0.91</b>	<b>56</b>	<b>-0.06 (-0.43 to 0.31)</b>	<b>0.76</b>
Jumping	19	-0.04 (-0.67 to 0.60)	0.91	46	-0.04 (-0.45 to 0.37)	0.86	19	-0.03 (-0.67 to 0.60)	0.92
Cycle erg PPO	37	0.13 (-0.33 to 0.58)	0.58	44	0.07 (-0.35 to 0.49)	0.74	37	-0.07 (-0.53 to 0.38)	0.76
RFD	23	0.12 (-0.45 to 0.70)	0.67	-	-	-	-	-	-

4 CI = confidence interval, MVC = maximum voluntary contraction, Isok = isokinetic, erg = ergometer, PPO = peak power output, RFD = rate of force

5 development

## 6 4. Discussion

7 The purpose of this systematic review was to collate and evaluate the literature that has investigated  
8 the effect of the menstrual cycle on strength-related measures in eumenorrhic women. Based upon  
9 the results of 21 studies that met the criteria for inclusion, differences between phases within the  
10 menstrual cycle for measures of MVC, IPT and explosive strength are regarded as trivial to small. The  
11 assessment of study quality revealed that a number of important features of study design were  
12 consistently overlooked. Small sample sizes, absence of hormonal measures to identify and verify  
13 menstrual cycle phase, lack of assessor blinding, poor control of confounding factors, and non-  
14 randomization of trials is likely to explain the inconsistent findings in this area. Future investigations  
15 should endeavour to address the important methodological issues highlighted here (Fig. 2).

16 Theoretically, maximal physical performance during the menstrual cycle is at its lowest during  
17 menstruation and/or the luteal phase<sup>3</sup>. The results of the meta-analyses conducted in this review  
18 largely refute this suggestion. For the majority of studies that were entered into the meta-analyses,  
19 results displayed a high level of similarity between menstrual cycle phases, as demonstrated by  
20 narrow 95% CIs, and low heterogeneity values ( $p \geq 0.83$ ,  $I^2 = 0\%$ ). For the phases of the menstrual cycle  
21 that were compared, fluctuations in hormones have, at most, a small effect ( $ES \leq 0.35$ ) upon strength  
22 performance. Although a similar pattern of results was observed across the investigations in this  
23 review, a number of studies did note significant ( $p < 0.05$ ) and/or moderate differences ( $ES \geq 0.6$ )  
24 between phases<sup>30,35,37,39,45</sup>. The reasons for these discrepancies are likely to be multi-factorial, thus it is  
25 important to discuss these anomalies in the context of other findings and the results of the assessment  
26 of study quality.

27 The inclusion of reliability statistics for dependent variables when reporting study outcomes is  
28 recommended<sup>51</sup>, however these were only provided in eight studies<sup>32,34-36,39,42,43,50</sup>. Reliability was  
29 generally reported as being high in most studies (intra-class correlation coefficient  $> 0.9$ )<sup>34-36,42</sup> and the  
30 coefficient of variation has been reported at  $< 6\%$  for the tasks used in the studies<sup>43,52,53</sup>. It is therefore  
31 likely that the trivial-small differences ( $ES < 0.4$ ) observed in strength values between phases in many



32 studies can be explained by random error. Furthermore, a number of the statistically significant  
33 differences identified in several studies<sup>30,35,45</sup> were trivial or small in magnitude (<5%, ES<0.3), and  
34 fell within the 95% CI for the phases compared. Additionally, six studies did not report with sufficient  
35 accuracy the reliability of the assays used to evaluate different hormone concentrations<sup>37,38,44,46,48,50</sup>,  
36 therefore it is unknown the extent to which the differences observed in hormones in these studies can  
37 be attributed to measurement error.

38 The number of participants used in many studies included in this review was small (mean:  $n=11$ ).  
39 Several studies provided statistical verification that the sample size was sufficiently powered to detect  
40 meaningful changes<sup>32,34,35,43</sup>, however this calculation was not always based upon the strength variable  
41 measured<sup>34</sup>. Other studies did not include a power calculation; therefore, it is likely that for a number  
42 of the studies included in this review, sample sizes may not have been adequate to detect differences  
43 in strength values.

44 Accurate determination of the days within the menstrual cycle to test each participant is a critical  
45 aspect of research in this area<sup>3</sup>. Inconsistencies between studies may therefore, in part, be attributed to  
46 the methods used to determine the most appropriate day to test strength-status within these phases,  
47 and the actual day selected. All included studies estimated hormonal status by counting days from  
48 self-reported menstruation onset. Many studies employed urinary ovulation tests to detect a surge in  
49 LH<sup>30-32,34,35,37,42,46</sup>, and/or monitoring of basal body temperature<sup>30,32,36,38-40,43,49,50</sup>, in the cycle prior to  
50 data collection to identify the idiosyncrasies in hormone fluctuations that were subsequently used to  
51 assist with the scheduling of tests for each participant. This may, in part, ameliorate the limitations  
52 associated with testing only within a single cycle. However, it is well-established that substantial  
53 variability exists in menstrual cycle lengths and timing of phases in eumenorrheic women<sup>7</sup>, thus  
54 targeting specific days beyond menses onset and/or ovulation, may not capture the phases with  
55 sufficient accuracy<sup>54</sup>. Although false-positive results are rare with urinary LH tests, these rely on  
56 participants conducting the test correctly and interpreting results accurately, which may not always be  
57 the case<sup>54</sup>. In studies that did not rely upon urinary testing or tracking of basal body temperature to

58 estimate ovulation<sup>33,41,44,45,47,48</sup>, the likelihood of including participants in the data collection with an  
59 anovulatory cycle is increased.

60 Most investigations also assessed hormone concentrations on the day of testing using a  
61 blood<sup>32,33,47,48,50,34–38,42–44</sup>, saliva<sup>41,45</sup> or urine sample<sup>46</sup> to verify that differences existed between time-  
62 points. Nevertheless, it is problematic to determine from a single measurement whether the hormone  
63 was rising, peaking or falling, particularly during the ovulatory phase, where the rise in oestrogen  
64 concentration is short-lived. Five studies did not ascertain hormonal concentrations alongside strength  
65 testing trials<sup>30,31,39,40,49</sup>. Consequently, some uncertainty exists over whether the hormonal milieu  
66 differed between measurements, despite proxy physiological measures being used to identify  
67 appropriate time-points. Additionally three investigations, that did not aim to measure strength during  
68 the ovulatory phase, measured only progesterone<sup>36,44,48</sup>, thus the role of oestrogen in explaining the  
69 patterns of results observed in these studies cannot be discerned. It is also noteworthy that three of the  
70 five studies<sup>30,39,45</sup> that observed significant differences between phases included a greater number of  
71 time points (four or five), compared to the smaller number of time points (two or three) measured in  
72 14 of the studies observing no significant differences. A greater number of trials across the menstrual  
73 cycle may therefore have captured subtle differences between important phases, which studies with  
74 fewer measurement points may have missed.

75 Research in this area is potentially confounded by high levels of inter-individual variability in  
76 hormonal concentrations across the menstrual cycle<sup>7</sup>. This is illustrated in the study by Cook and co-  
77 workers<sup>41</sup>, which reported significantly higher changes in testosterone values across the menstrual  
78 cycle in elite female athletes compared to a group of non-elite but active females. Indeed, training  
79 alters the level of circulating androgens<sup>55</sup> and ovarian hormones<sup>56</sup> during the menstrual cycle, thus  
80 strength status through the menstrual cycle in well-trained females may differ from that of untrained  
81 females. Training status was not used as a moderating variable in the meta-analyses due to the lack of  
82 detail provided on strength-training history for participants in most studies. Highly- or well-trained  
83 athletes were used in a number of investigations<sup>41,45–48</sup>, but it was often unclear how much strength-  
84 training experience participants possessed.

85 Despite several studies recognizing the issue of individuality<sup>32,47,50</sup>, there are currently no  
86 investigations that have attempted to objectively quantify the degree to which observed differences in  
87 strength between menstrual cycle phases, are individual in nature. Within the context of personalized  
88 medicine and exercise programming, a study of this nature would be valuable. A robust  
89 methodological and statistical approach to addressing this important issue would involve repeated  
90 measurements in a randomized order over two menstrual cycles<sup>57</sup>. Although two existing studies  
91 duplicated measures over two menstrual cycles<sup>41,42</sup>, individual differences were not quantified.

92 The nature of the strength task and muscle groups tested might also be factors that explain the  
93 ambiguity in results, however the findings from this meta-analysis refute this (Table 1). The IPT knee  
94 flexor sub-category produced the greatest ES for the comparison between early-follicular phase and  
95 ovulatory phase, with the 95% CI extending to a moderate difference in the direction of the early-  
96 follicular phase ( $p=0.34$ ,  $ES=-0.35$ , 95% CI: -1.07 to 0.37). However, it is important to note that this  
97 sub-analysis comprised only one study ( $n=15$ ), therefore more data are required to provide a firmer  
98 conclusion.

99 Potential confounding factors were adequately controlled in ten of the 21 studies (Fig. 2). In  
100 particular, standardizing the time of day that trials are conducted is important, because ovarian  
101 hormones are known to have a diurnal variation, with progesterone<sup>58</sup>, estradiol and testosterone  
102 concentrations<sup>59</sup> highest in the morning, and gradually decreasing throughout the day. Around half of  
103 the studies conducted tests in a fully randomized or quasi-randomized sequence<sup>32,33,49,36,38-41,43-45</sup>. A  
104 non-randomized order was applied in the other studies, which typically involved sequencing tests  
105 chronologically, starting from the onset of menses (day 0). This approach to study organization brings  
106 ‘design bias’, which is inconsistent with the principle of equipoise, and raises the possibility that a  
107 degree of systematic bias exists in the results of studies. In particular, for non-strength trained females  
108 who were unfamiliar with a strength task, a learning effect is likely to occur, which benefits the trials  
109 taking place later in the study<sup>51</sup>. Appropriate randomization of trials also facilitates *no a priori*  
110 knowledge amongst the researchers of a participants menstrual cycle phase. Knowledge of the  
111 participants hormonal status at the time of a test generates a cognitive bias that may influence

112 behaviour and creates self-deception<sup>60</sup>. Although fully blinding the participant to their menstrual cycle  
113 phase would be impossible, the absence of a single-blind design may also have contributed to the  
114 conflicting findings reported in this review.

115 There are several limitations associated with this review that should be recognized. We addressed  
116 variations in strength status in eumenorrheic females only, however it should be recognized that a  
117 high number (~30-50%) of active females use hormonal contraceptives<sup>61</sup>, which contain exogenous  
118 hormones that may influence physical performance and adaptation to training<sup>62</sup>. A review that  
119 captures this group of females would potentially be useful but is beyond the scope of a single article.  
120 In addition to the numerous confounding factors that influence the results in this area of research,  
121 there was also a high level of inconsistency in the number and choice of time points used to compare  
122 strength, making inter-study comparison problematic. Even within the phases used for comparison in  
123 the meta-analysis, timings of measurements varied across studies, which within the context of rapidly  
124 shifting concentrations of hormones, is likely to have influenced the results. Six studies only took  
125 measurements at two time points<sup>32,34,40,43,44,47</sup> and three of these studies scored the highest in the  
126 quality assessment ( $\geq 10$  out of 15 points)<sup>32,34,43</sup>. It is therefore intriguing what additional insight these  
127 higher quality studies could have provided had more phases been selected for testing. Finally, at the  
128 eligibility stage of the systematic review, 40 studies were excluded. Although there were validity-  
129 related issues within these studies that precluded their inclusion in the review, there may have been  
130 important results contained in some studies that were worthy of consideration in this analysis.

## 131 **5. Conclusion**

132 Strength-related characteristics appear to remain invariable between menstrual cycle phases, despite  
133 fluctuations in concentrations of circulating levels of oestrogen and progesterone. Practically, these  
134 findings suggest that eumenorrheic females participating in sports or activities that rely heavily on  
135 maximal or explosive strength, are not disadvantaged by their menstrual cycle phase on any given  
136 day. Research in this area is immensely challenging due to problems associated with accurate  
137 identification of cycle phases in each participant and control of other confounding factors that may

138 also cause variations in strength performance. Consequently, many of the studies in this area are  
139 limited by small sample sizes and methodological issues, therefore future experiments should  
140 endeavour to address these shortcomings.

141

## 142 **6. Practical Implications**

- 143 • Fluctuations in female sex hormones over the course of the menstrual cycle may explain  
144 variations in physical performance
- 145 • Strength-related qualities are minimally affected by changes in sex hormones over the course of  
146 the menstrual cycle
- 147 • Regularly menstruating females who participate in strength-related exercise activities or  
148 strength-dominant sports do not need to adjust for menstrual cycle phase to maximize their  
149 performance

150

151

152 **References**

- 153 1 Dawson EA, Reilly T. Menstrual cycle, exercise and health. *Biol Rhythm Res* 2009; 40(1):99–  
154 119.
- 155 2 Constantini NW, Dubnov G, Lebrun CM. The menstrual cycle and sport performance. *Clin*  
156 *Sports Med* 2005; 24(2):e51–e82.
- 157 3 de Jonge XAKJ. Effects of the menstrual cycle on exercise performance. *Sport Med* 2003;  
158 33(11):833–851.
- 159 4 Lebrun CM, Joyce SM, Constantini NW. Effects of female reproductive hormones on sports  
160 performance. In: Constantini Naama, Hackney A C, editors. *Endocrinol. Phys. Act. Sport*.  
161 Totowa, NJ, Humana Press, 2013. p. 281–322.
- 162 5 Tenan M, Hackney AC. Sex hormones and the nervous system, do they matter for physical  
163 performance? *J Sci Med Sport* 2017; 20:S14.
- 164 6 Davis SR, Wahlin-Jacobsen S. Testosterone in women—the clinical significance. *Lancet*  
165 *Diabetes Endocrinol* 2015; 3(12):980–992. Doi: 10.1016/S2213-8587(15)00284-3.
- 166 7 Haggstrom M. Reference ranges for estradiol, progesterone, luteinizing hormone and follicle-  
167 stimulating hormone during the menstrual cycle. *WikiJournal Med* 2014; 1(1):1.
- 168 8 Hansen M. Female hormones: do they influence muscle and tendon protein metabolism? *Proc*  
169 *Nutr Soc* 2018; 77(1):32–41.
- 170 9 Stoffel-Wagner B. Neurosteroid metabolism in the human brain. *Eur J Endocrinol* 2001;  
171 145(6):669–680.
- 172 10 Wolf OT, Kirschbaum C. Actions of dehydroepiandrosterone and its sulfate in the central  
173 nervous system: effects on cognition and emotion in animals and humans. *Brain Res Rev* 1999;  
174 30(3):264–288.

- 175 11 Schultz KN, Silke A, Hu M, et al. Viral vector-mediated overexpression of estrogen receptor- $\alpha$   
176 in striatum enhances the estradiol-induced motor activity in female rats and estradiol-  
177 modulated GABA release. *J Neurosci* 2009; 29(6):1897–1903.
- 178 12 Smith SS, Woolley CS. Cellular and molecular effects of steroid hormones on CNS  
179 excitability. *Cleve Clin J Med* 2004; 71(2):S4.
- 180 13 Callachan H, Cottrell GA, Hather NY, et al. Modulation of the GABAA receptor by  
181 progesterone metabolites. *Proc R Soc London Ser B Biol Sci* 1987; 231(1264):359–369.
- 182 14 Bateup HS, Booth A, Shirtcliff EA, et al. Testosterone, cortisol, and women's competition.  
183 *Evol Hum Behav* 2002; 23(3):181–192.
- 184 15 Estrada M, Espinosa A, M ller M, et al. Testosterone stimulates intracellular calcium release  
185 and mitogen-activated protein kinases via a G protein-coupled receptor in skeletal muscle  
186 cells. *Endocrinology* 2003; 144(8):3586–3597.
- 187 16 de Mouzon J, Testart J, Lefevre B, et al. Time relationships between basal body temperature  
188 and ovulation or plasma progestins. *Fertil Steril* 1984; 41(2):254–259.
- 189 17 Franssen H, Wieneke GH. Nerve conduction and temperature: necessary warming time.  
190 *Muscle and Nerve* 1994; 17(3):336–344.
- 191 18 Oksa J, Rintamäki H, Mäkinen T, et al. Cooling-induced changes in muscular performance and  
192 EMG activity of agonist. *Aviat Space Environ Med* 1995; 66(1):26–31.
- 193 19 Goodwin JE, Cleather DJ. The biomechanical principles underpinning strength and  
194 conditioning . In: Jeffreys Ian, Moody Jeremy A, editors. *Strength Cond. Sport. Perform.*  
195 London, UK, Routledge, 2016.
- 196 20 Shaw BS, Shaw I, Brown GA. Resistance exercise is medicine: Strength training in health  
197 promotion and rehabilitation. *Int J Ther Rehabil* 2015; 22(8):385–389.

- 198 21 McKinnon NB, Connelly DM, Rice CL, et al. Neuromuscular contributions to the age-related  
199 reduction in muscle power: mechanisms and potential role of high velocity power training.  
200 *Ageing Res Rev* 2017; 35:147–154.
- 201 22 Lauersen JB, Bertelsen DM, Andersen LB. The effectiveness of exercise interventions to  
202 prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials.  
203 *Br J Sport Med* 2014; 48(11):871–877. Doi: 10.1136/bjsports-2013-092538.
- 204 23 Seitz LB, Reyes A, Tran TT, et al. Increases in lower-body strength transfer positively to  
205 sprint performance: a systematic review with meta-analysis. *Sport Med* 2014; 44(12):1693–  
206 1702.
- 207 24 Folland JP, Williams AG. The Adaptations to Strength Training. *Sport Med* 2007; 37(2):145–  
208 168. Doi: 10.2165/00007256-200737020-00004.
- 209 25 Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among  
210 female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg*  
211 2005; 18(1):82–88.
- 212 26 Tenan MS. Sex hormone effects on the nervous system and their impact on muscle strength  
213 and motor performance in women. In: Hackney A C, editor. *Sex Horm. Exerc. Women*.  
214 Switzerland, Springer International Publishing , 2017. p. 59–70.
- 215 27 Ghogomu EAT, Maxwell LJ, Buchbinder R, et al. Updated method guidelines for cochrane  
216 musculoskeletal group systematic reviews and metaanalyses. *J Rheumatol* 2014; 41(2):194–  
217 205.
- 218 28 Ouzzani M, Hammady H, Fedorowicz Z, et al. Rayyan-a web and mobile app for systematic  
219 reviews. *Syst Rev* 2016; 5(1):210. Doi: 10.1186/s13643-016-0384-4.
- 220 29 Stevens JR, Taylor AM. Hierarchical dependence in meta-analysis. *J Educ Behav Stat* 2009;  
221 34(1):46–73. Doi: 10.3102/1076998607309080.



- 222 30 Bambaiechi E, Reilly T, Cable NT, et al. The isolated and combined effects of menstrual cycle  
223 phase and time-of-day on muscle strength of eumenorrheic females. *Chronobiol Int* 2004;  
224 21(4–5):645–660.
- 225 31 Drake SM, Evetovich T, Eschbach C, et al. A pilot study on the effect of oral contraceptives  
226 on electromyography and mechanomyography during isometric muscle actions. *J*  
227 *Electromyogr Kinesiol* 2003; 13(3):297–301. Doi: 10.1016/S1050-6411(03)00024-5.
- 228 32 Elliott KJ, Cable NT, Reilly T, et al. Effect of menstrual cycle phase on the concentration of  
229 bioavailable 17-beta oestradiol and testosterone and muscle strength. *Clin Sci* 2003;  
230 105(6):663–669. Doi: 10.1042/CS20020360.
- 231 33 Okudan N, Gökbel H, Üçok K, et al. Serum leptin concentration and anaerobic performance do  
232 not change during the menstrual cycle of young females. *Neuroendocrinol Lett* 2005;  
233 26(4):297–300.
- 234 34 Bell DR, Blackburn JT, Ondrak KS, et al. The effects of oral contraceptive use on muscle  
235 stiffness across the menstrual cycle. *Clin J Sport Med* 2011; 21(6):467–473.
- 236 35 Ekenros L, Hirschberg AL, Heijne A, et al. Oral Contraceptives Do Not Affect Muscle  
237 Strength and Hop Performance in Active Women. *Clin J Sport Med* 2013; 23(3):202–207.  
238 Doi: 10.1097/JSM.0b013e3182625a51.
- 239 36 Giacomoni M, Bernard T, Gavarry O, et al. Influence of the menstrual cycle phase and  
240 menstrual symptoms on maximal anaerobic performance. *Med Sci Sports Exerc* 2000;  
241 32(2):486–492. Doi: 10.1097/00005768-200002000-00034.
- 242 37 Iwamoto Y, Kubo J, Masamitsu I, et al. Variation in maximal voluntary contraction during the  
243 menstrual cycle. *Japanese J Phys Fit Sport Med* 2002; 51:193–202.
- 244 38 Kubo K, Miyamoto M, Tanaka S, et al. Muscle and tendon properties during menstrual cycle.  
245 *Int J Sport Med* 2009; 30(02):139–143.

- 246 39 Tenan MS, Hackney AC, Griffin L. Maximal force and tremor changes across the menstrual  
247 cycle. *Eur J Appl Physiol* 2016; 116(1):153–160. Doi: 10.1007/s00421-015-3258-x.
- 248 40 Birch K, Reilly T. The diurnal rhythm in isometric muscular performance differs with  
249 eumenorrheic menstrual cycle phase. *Chronobiol Int* 2002; 19(4):731–742.
- 250 41 Cook CJ, Kilduff LP, Crewther BT. Basal and stress-induced salivary testosterone variation  
251 across the menstrual cycle and linkage to motivation and muscle power. *Scand J Med Sci*  
252 *Sports* 2018; 28(4):1345–1353. Doi: 10.1111/sms.13041.
- 253 42 Fridén C, Hirschberg AL, Saartok T. Muscle strength and endurance do not significantly vary  
254 across 3 phases of the menstrual cycle in moderately active premenopausal women. *Clin J*  
255 *Sport Med* 2003; 13(4):238–241.
- 256 43 Lebrun CM, McKenzie DC, Prior JC, et al. Effects of menstrual cycle phase on athletic  
257 performance. *Med Sci Sport Exerc* 1995; 27(3):437–444.
- 258 44 Middleton LE, Wenger HA. Effects of menstrual phase on performance and recovery in  
259 intense intermittent activity. *Eur J Appl Physiol* 2006; 96(1):53–58. Doi: 10.1007/s00421-005-  
260 0073-9.
- 261 45 Gordon D, Hughes F, Young K, et al. The effects of menstrual cycle phase on the development  
262 of peak torque under isokinetic conditions. *Isokinet Exerc Sci* 2013; 21(4):285–291. Doi:  
263 10.3233/IES-130499.
- 264 46 Hertel J, Williams NI, Olmsted-Kramer LC, et al. Neuromuscular performance and knee laxity  
265 do not change across the menstrual cycle in female athletes. *Knee Surgery, Sport Traumatol*  
266 *Arthrosc* 2006; 14(9):817–822. Doi: 10.1007/s00167-006-0047-4.
- 267 47 Julian R, Hecksteden A, Fullagar HHK, et al. The effects of menstrual cycle phase on physical  
268 performance in female soccer players. *PLoS One* 2017; 12(3):e0173951. Doi:  
269 10.1371/journal.pone.0173951.

270 48 Tounsi M, Jaafar H, Aloui A, et al. Soccer-related performance in eumenorrheic Tunisian  
271 high-level soccer players: effects of menstrual cycle phase and moment of day. *J Sports Med*  
272 *Phys Fitness* 2018; 58(4):497–502. Doi: 10.23736/S0022-4707.17.06958-4.

273 49 Birch KM, Reilly T. Manual handling performance: the effects of menstrual cycle phase.  
274 *Ergonomics* 1999; 42(10):1317–1332.

275 50 de Jonge XAKJ, Boot CRL, Thom JM, et al. The influence of menstrual cycle phase on  
276 skeletal muscle contractile characteristics in humans. *J Physiol* 2001; 530(1):161–166. Doi:  
277 10.1111/j.1469-7793.2001.0161m.x.

278 51 Hopkins WG. Measures of reliability in sports medicine and science. *Sport Med* 2000;  
279 30(1):1–15.

280 52 McMaster DT, Gill N, Cronin J, et al. A brief review of strength and ballistic assessment  
281 methodologies in sport. *Sport Med* 2014; 44(5):603–623.

282 53 Molczyk L, Thigpen LK, Eickhoff J, et al. Reliability of Testing the Knee Extensors and  
283 Flexors in Healthy Adult Women Using a Cybex<sup>®</sup> II Isokinetic Dynamometer. *J Orthop Sport*  
284 *Phys Ther* 1991; 14(1):37–41. Doi: 10.2519/jospt.1991.14.1.37.

285 54 Wideman L, Montgomery MM, Levine BJ, et al. Accuracy of calendar-based methods for  
286 assigning menstrual cycle phase in women. *Sport Heal A Multidiscip Approach* 2013;  
287 5(2):143–149. Doi: 10.1177/1941738112469930.

288 55 Enea C, Boisseau N, Fargeas-Gluck MA, et al. Circulating androgens in women. *Sport Med*  
289 2011; 41(1):1–15. Doi: 10.2165/11536920-000000000-00000.

290 56 Timon R, Corvillo M, Brazo J, et al. Strength training effects on urinary steroid profile across  
291 the menstrual cycle in healthy women. *Eur J Appl Physiol* 2013; 113(6):1469–1475. Doi:  
292 10.1007/s00421-012-2575-6.

293 57 Senn S. Mastering variation: variance components and personalised medicine. *Stat Med* 2016;  
294 35(7):966–977. Doi: 10.1002/sim.6739.

295 58 Syrop CH, Hammond MG. Diurnal variations in midluteal serum progesterone measurements.  
296 *Fertil Steril* 1987; 47(1):67–70. Doi: 10.1016/S0015-0282(16)49937-1.

297 59 Panico S, Pisani P, Muti P, et al. Diurnal variation of testosterone and estradiol: a source of  
298 bias in comparative studies on breast cancer. *J Endocrinol Invest* 1990; 13(5):423–426. Doi:  
299 10.1007/BF03350695.

300 60 Munafò MR, Nosek BA, Bishop DVM, et al. A manifesto for reproducible science. *Nat Hum*  
301 *Behav* 2017; 1(1):21.

302 61 Martin D, Sale C, Cooper SB, et al. Period prevalence and perceived side effects of hormonal  
303 contraceptive use and the menstrual cycle in elite athletes. *Int J Sport Physiol Perform* 2018;  
304 13(7):926–932.

305 62 Burrows M, Peters CE. The influence of oral contraceptives on athletic performance in female  
306 athletes. *Sport Med* 2007; 37(7):557–574.

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**Supplementary Table.** Participant characteristics, main study design features and results of studies that have investigated variability in strength-related measures through the menstrual cycle.

Authors; country of origin	n	Age (y)	Training status	Phase identification / hormone verification	Measures	Timing of measurements	Main findings	Quality score (0-15)
<i>Studies showing significant differences</i>								
Bambaeichi et al. (2004); U.K.	8	30 ± 5	Sedentary	Self-report menses; oral temp; urine / -	Knee ext and flex isok (60, 180°.s <sup>-1</sup> ): peak torque Knee ext and flex: MVC (at 60°)	Menses+1-4d, mid-FP (+7-9d), OP, mid-LP (+19-21d), late-LP (+25-27d); Measures taken 06:00h and 18:00h.	Time of day effect: NSD, ES=0.20  Knee ext torque 180°.s <sup>-1</sup> : OP sig higher (p<0.05) than menses (ES=0.22, 4.7%), mid-LP sig higher (p<0.05) than menses (ES=0.25, 4.8%) & mid-FP (ES=0.34, 6.2%)  Knee flex torque 60°.s <sup>-1</sup> : OP sig higher (p<0.05) than mid-FP (ES=0.53, 9.1%) & mid-LP (ES=0.49, 9.4%)  Knee flex MVC: OP sig higher (p<0.05) than mid-FP (ES=0.27, 6.5%) & mid-LP (ES=0.39, 10.2%)  Knee ext torque 60°.s <sup>-1</sup> , knee flex torque 180°.s <sup>-1</sup> , knee ext MVC: NSD, ES<0.2	7
Ekenros et al. (2013); Sweden	9	27 ± 5	Recreational (2 sessions per week)	Self-report menses; urine / blood	Knee ext isok (120°.s <sup>-1</sup> ): peak torque Handgrip: MVC 1-leg hop distance	Menses+2-4d, OP (within 48h of peak LH), LP (ovulation+7-8d)	Knee ext torque: LP sig higher (p=0.02) than menses (ES=0.22, 4.3%), NSD (ES<0.2) between other phases and MVC and hop	10
Gordon et al. (2013); U.K.	11	21 ± 1	Well-trained	Self-report menses / saliva	Knee ext and flex isok: 60, 120, 180, 240°.s <sup>-1</sup>	Menses+1-3d, mid-FP (+9-11d), mid-LP (+19-20d), pre-menses (+27-28d)	Knee ext 60, 180, 240°.s <sup>-1</sup> : NSD, ES=0.15-0.28 between phases 120°.s <sup>-1</sup> : mid-LP sig higher (p=0.02) than menses (ES=0.15, 2.9%)  Knee flex 180, 240°.s <sup>-1</sup> : NSD, ES=0.13-0.33 between phases	9

							60°.s <sup>-1</sup> : pre-menses sig higher (p=0.02) than menses (ES=0.47, 14.2%) 120°.s <sup>-1</sup> : pre-menses sig higher (p=0.02) than menses (ES=0.37, 8.9%)	
Iwamoto et al. (2002); Japan	6	22 ± 4	Active	Self-report menses; urine / blood	Elbow flexion (90°): MVC	Menses (+1-3d), OP (+11-13d), LP (+21-23d)	MVC: OP sig higher than menses (p<0.05, ES=0.46, 12.7%) and LP (p<0.01, ES=0.72, 21.1%)	7
Tenan et al. (2016); U.S.A.	9	25 ± 5	Recreational	Self-report menses; oral temp / -	Knee ext (90°): MVC	Early-FP, late-FP, OP, mid-LP, late-LP (individualized)	MVC: sig diff across cycles (p<0.01). Mid-LP sig lower than late-FP (p=0.01, ES=0.58, 16.9%), OP (p=0.02, ES=0.55, 16.9%), late-LP (p<0.01, ES=0.65, 18.5%) Early-FP v mid-LP: NSD (ES=0.44, 13.9%), favour early-FP	10
<b><i>Studies showing non-significant differences</i></b>								
Bell et al. (2011); U.S.A.	15	20 ± 2	Physically active	Self-report menses; urine / blood	Prone knee flex 30°: RFD, time to peak force <sub>50%</sub>	Menses+3-5d Ovulation+2-4d	RFD and peak force <sub>50%</sub> : NSD, ES<0.2	11
Birch and Reilly (1999); U.K.	17	18-32	Not reported	Self-report menses; oral temp / -	Rack pull: MVC @knee and waist height	Menses, mid-FP, within 48h of ovulation, mid-LP, pre-menses	MVC @knee: NSD, OP vs mid-LP: ES=0.22 (favour LP), other comparisons ES<0.2	6
Birch and Reilly (2002); U.K.	10	24 ± 3	Moderately active	Self-report menses; oral temp / -	Rack pull: MVC @knee height	Mid-FP, mid-LP Measures taken 06:00h and 18:00h	MVC: phase x time of day interaction (p<0.05) 06:00: NSD, ES=0.20 (favour mid-FP) 18:00: NSD, ES=0.16 (favour mid-LP)	8
Cook et al. (2018); U.K.	22	21 ± 1	6 elite athletes, 16 non-elite; multi-sport; >2y RT	Self-report menses / saliva	Static cycle: peak power	Menses+7d, +14d, +21d	Peak power: NSD 7d v 14d: ES=0.07 14d v 21d: ES=0.09 7d v 21d: ES=0.01	9

de Jonge et al. (2001); Australia	15	30 ± 8	Not reported	Self-report menses; oral temp / blood	Knee ext: MVC and Knee ext and flex isok (60, 240°.s <sup>-1</sup> ): peak torque  Handgrip: MVC	Menses (+1-3d), late-FP (pre-ovulation), LP	Handgrip and knee ext MVC, peak torque 60°.s <sup>-1</sup> , 240°.s <sup>-1</sup> : NSD, ES<0.2  Knee flex 60°.s <sup>-1</sup> : NSD, menses v late-FP: ES=0.41 (favour menses) Knee flex 240°.s <sup>-1</sup> : NSD, menses v late-FP: ES=0.29 (favour menses)	6
Drake et al. (2003); U.S.A.	7	24 ± 1	Sedentary	Self-report menses; urine / -	Knee ext 45°: MVC	Menses(+1-3d), early-FP (+4-7d), late-FP (+9-11d), OP, early-LP (ovulation+5d)	MVC: NSD between any phase Early-FP v early-LP: ES=0.25 (favour early-FP) Early-FP v menses: ES=0.22 (favour early-FP) Other comparisons ES<0.2	6
Elliott et al. (2003); U.K.	7	25 ± 5	Sedentary*	Self-report menses; urine and oral temp / blood	First dorsal interosseous: MVC	Early FP (menses+2d), mid-LP (+21d)	MVC: NSD (p=0.1), ES=0.43, 9.2% (favour mid-LP)	13
Fridén et al. (2003); Sweden	10	25 ± 4	Moderately active	Self-report menses; urine / blood	Handgrip: MVC Knee ext isok (120°.s <sup>-1</sup> ): peak torque 1-leg hop distance	Early-FP (menses+3-5d), OP (LH surge), mid-LP (ovulation+7d); 2 cycles	MVC: NSD between phases, OP v LP: ES=0.27 (favour LP)  Peak torque: p=0.06 between phases, FP v LP: ES=0.36 (favour LP)  1-leg hop: NSD, all ES=0.07	10
Giacomini et al. (2000); France	7	23 ± 3	Physically active	Self-report menses; rectal temp / blood	Cycle ergometer: peak power, optimal force Multi-jumps: peak power Squat jump height	Menses (+1-4d), mid-FP (+7-9d), mid-LP (+19-21d)	Cycle power: NSD between phases, menses v mid-FP: ES=0.24 (favour mid-FP)  Multi-jump: NSD between phases, ES<0.2  Squat jump: NSD (p=0.48) between phases, menses v mid-FP: ES=0.31 (favour mid-FP)	11

Hertel et al. (2006); U.S.A.	14	19 ± 1	Collegiate athletes (soccer or cheer-leading)	Self-report menses; urine / urine	Knee ext and flex isok (120°.s <sup>-1</sup> ): peak torque	Mid-FP (menses+4-7d), OP (ovulation±2d), mid-LP (ovulation+7-10d)	Knee ext: NSD, mid-FP v OP: ES=0.40 mid-FP v mid-LP: ES=0.31  Knee flex: NSD, mid-FP v OP: ES=0.36 mid-FP v mid-LP: ES=0.41	8
Julian et al. (2017); Germany	9	19 ± 4	Sub-elite soccer players	Self-report menses / blood	CMJ	Mid-FP (menses+5-7d), mid-LP (+21-22d)	NSD; ES=0.17	8
Kubo et al. (2009); Japan	8	23 ± 1	Sedentary or mild-moderately active	Self-report menses; oral temp / blood	Knee ext and plantar flex: MVC, time to peak torque	Menses (+1-3d), OP (ovulation±2d), LP (ovulation+7-10d)	Knee ext and plantar flex MVC: NSD, ES<0.2 Knee ext time to peak: NSD, OP v LP: ES=0.35 (favour LP) Plantar flex time to peak: NSD, menses v LP: ES=0.38 (favour menses)	9
Lebrun et al. (1995); Canada	16	28 ± 4	Aerobically trained athletes (multi-sport)	Self-report menses; oral temp / blood	Knee ext and flex (30°.s <sup>-1</sup> ): peak torque (R and L)	Early FP (menses+3-8d), mid-LP (ovulation+4-9d)	Knee ext and flex (R and L): NSD Flex R: ES=0.71, Flex L: ES=0.22 (both favour mid-LP)	11
Middleton & Wenger (2006); Canada	6	25 ± 3	Moderately active	Self-report menses / blood	Cycle ergometer 10x6s sprint (30s rec): peak power	FP (menses+6-10d), LP (+20-24d)	Peak power: NSD, ES=0.17	9
Okudan et al. (2005); Turkey	15	19-23	Sedentary	Self-report menses / blood	Cycle ergometer Wingate test: peak power	Menses+7d, +14d, +21d	NSD 7d v 14d: ES=0.22 (favour 14d)	8
Tounsi et al. (2018); Tunisia	11	21 ± 3	High-level soccer	Self-report menses / blood	5-step bounds	Menses (+2-4d), mid-FP (+7-9d), LP (+20-22d). Each (am) and (pm)	Cycle phase (am): NSD, Menses v LP: ES=0.44 (favour menses); mid-FP v LP: ES=0.33 (favour mid-FP)  (pm): NSD, ES<0.15	8



temp = temperature, d = days after the beginning of menstrual bleeding, h = hours, ext = extension, flex = flexion, isok = isokinetic, NSD = no significant difference, MVC = maximal voluntary contraction, FP = follicular phase, OP = ovulatory phase, LP = luteal phase, ES = effect size (Hedges g), sig = significant, RFD = rate of force development, RT = resistance training, LH = luteinizing hormone, reps = repetitions, CMJ = counter-movement jump, R = right side, L = left side, rec = recovery, \* obtained from Elliott et al. (2005)

Accepted