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The effects of menstrual cycle phases on postural balance, vestibulo-ocular reflex, and dual-task virtual reality performance in healthy young women

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Abstract

Purpose This study investigated the effects of hormonal fluctuations across the menstrual cycle on oculomotor function, vestibulo-ocular reflex (VOR), postural balance, and dual-task virtual reality (VR) performance in healthy young women. The primary objective was to compare these parameters between the early menstrual and post-menstrual phases.

Methods Twenty eumenorrheic females aged 18–25 were assessed during two phases: early menstrual (days 1–3) and post-menstrual (day 7+). Assessments included videonystagmography (VNG) for oculomotor evaluations (saccades, smooth pursuit, optokinetic responses), video head impulse testing (vHIT) for VOR gains in all semicircular canals, static and dynamic balance tests and a dual-task VR activity involving visual tracking and full-body movement. subjective symptoms were assessed using the Menstrual Symptom Questionnaire (MSQ) and a cybersickness scale. Wilcoxon signed-rank tests were used for comparisons. Wilcoxon signed-rank test was used for comparisons.

Results Oculomotor parameters and VOR gains showed no significant differences between phases. However, postural balance improved significantly post-menstrually in Single Leg Foam ($p = .003$), Walk on Foam ($p = .034$), and TUG ($p < .001$). Dual-task VR performance scores were also significantly higher in the post-menstrual phase.

Conclusion While oculomotor and VOR responses remained stable, the early menstrual phase was associated with reduced postural performance and lower dual-task VR scores. Hormonal fluctuations during this period may transiently impair postural control and motor performance. Considering the timing of assessments in relation to the menstrual cycle may contribute to more accurate clinical interpretation and better-informed planning of rehabilitation when needed.

Keywords Menstrual cycle · Vestibulo-ocular reflex · Oculomotor function · Postural stability · Virtual reality · Cybersickness

Introduction

The menstrual cycle involves hormonal changes impacting various bodily systems including visual and vestibular functions. The visual and vestibular systems collaborate to facilitate balance and spatial orientation. This collaboration, known as visual-vestibular integration, is crucial for maintaining stable vision and effective motor responses. Disruptions in this integration can result in symptoms like dizziness and motion sickness [1].

The visual-vestibular system integrates signals from visual stimuli and the inner ear to ensure balance. The vestibular system detects head movements through its components, while the visual system continuously provides environmental context for motor coordination. Hormonal fluctuations, particularly of estrogen and progesterone, significantly impact sensory processing and neural activity in these systems [1, 2].

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Hormonal variations across the menstrual cycle are categorized into distinct phases: follicular (low hormones), ovulatory (peak estrogen), and luteal (high progesterone). Research indicates that the follicular phase is associated with decreased postural stability, indicating impaired visual-vestibular integration [2, 3]. Assessments using dynamic posturography and Sensory Organization Tests (SOT) reveal reduced utilization of somatosensory and vestibular inputs during this phase [4].

The ovulatory phase, with elevated estrogen, may enhance neural excitability, leading to modified balance strategies [2, 5]. In the luteal phase, increased progesterone correlates with a higher susceptibility to motion sickness and visual-vestibular conflicts, as evidenced by simulation and caloric tests [6, 7]. Additionally, vestibulo-ocular reflex (VOR) performance may decline during this phase, potentially causing dizziness and visual anomalies [8].

Rapid hormonal shifts in the premenstrual phase have been linked to diminished postural control and increased visual dependence, particularly in those with premenstrual syndrome [5, 9]. While certain vestibular functions, like VOR, are responsive to hormonal changes, others, such as vestibular-evoked myogenic potentials (VEMP), remain stable across phases, indicating selective modulation within vestibular pathways [10].

Hormonal variations also directly influence the visual system, with altered excitability in the visual cortex noted during the luteal phase, especially in individuals with premenstrual dysphoric disorder (PMDD), suggesting that estrogen and progesterone affect central sensory processing [11]. These sensory interactions become particularly relevant in immersive virtual reality settings, where users may experience cybersickness—also known as virtual reality sickness—a condition characterized by dizziness, nausea, visual discomfort, and balance instability resulting from visual–vestibular conflict.

Consequently, healthcare professionals and rehabilitation specialists ought to factor in the menstrual cycle when assessing and managing vestibular impairments. Customizing vestibular rehabilitation protocols to address cycle-related variations could enhance therapeutic outcomes and improve sensory compensation [12, 13].

The primary objective of this study is to examine the effects of menstrual cycle–related hormonal fluctuations on visual-vestibular integration and postural stability in healthy young women, through objective and subjective functional evaluations.

It is hypothesized that hormonal fluctuations during the premenstrual and early menstrual phases may negatively affect visual-vestibular integration and balance control in healthy young women, leading to decreased postural stability compared to the postmenstrual phase.

Material and method

This study was conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval was obtained from the XXX University Non-Interventional Clinical Research Ethics Committee (Decision No: 880; Date: 26.10.2023). All participants were informed in detail about the study's purpose, procedures, potential risks, and their right to withdraw at any time without penalty. Prior to data collection, each participant voluntarily signed a written Informed Consent Form.

An a priori power analysis was performed using G*Power software (version 3.1.9.7) to estimate the required sample size for a within-subjects design. A two-tailed paired-samples t-test was selected to compare two time points (menstrual and post-menstrual phases). With an assumed medium-to-large effect size ($d = 0.65$), an alpha level of 0.05, and a desired power of 0.80, the minimum required sample size was calculated as 20 participants. Accordingly, 20 healthy female participants were included in the study.

A total of twenty healthy female subjects, aged from 18 to 25 years, were incorporated into the investigation. The criteria for participant eligibility in this research mandated that subjects be healthy females within the specified age range, all of whom indicated the presence of regular menstrual cycles (spanning from 26 to 32 days). The inclusion criteria stipulated that participant had not utilized hormonal contraceptives or engaged in hormone therapy in the preceding six months, possessed no recognized visual impairments that might compromise testing, and had no clinically diagnosed neurological, neuromuscular, cardiovascular, or psychiatric disorders. Moreover, participants were required to have no prior history of migraine or other recurrent headache syndromes, and to be neither pregnant nor breastfeeding at the time of the study. Individuals exhibiting musculoskeletal limitations that could potentially impede head, neck, or limb mobility were excluded. Furthermore, to mitigate external variables influencing vestibular and balance assessments, participants were instructed to abstain from the consumption of alcohol, sedatives, stimulants, or psychoactive substances for a minimum of 48 h preceding the evaluation. Only those individuals capable of complete cooperation with all testing protocols and adherence to instructions were admitted.

Exclusion criteria were defined to include individuals with an irregular or absent menstrual cycle, the use of hormonal contraceptives within the preceding six months, and a confirmed diagnosis of migraine, recurrent tension-type headache, or photophobia. Furthermore, participants were disqualified if they had been diagnosed with any vestibular disorder—such as benign paroxysmal positional vertigo (BPPV), Meniere's disease, or vestibular neuritis—within

the previous six months. Additional exclusions were applied to individuals exhibiting active psychiatric disorders (e.g., depression, anxiety disorders, panic disorders), those utilizing medications that could potentially affect balance, sensory perception, or cognitive functioning, and individuals with any musculoskeletal disorders (e.g., scoliosis, cervical disc herniation) that could impede posture or movement. Uncorrected visual impairments and cardiopulmonary disorders (e.g., arrhythmia, orthostatic hypotension) were also considered sufficient grounds for exclusion. Lastly, individuals who were either unable or unwilling to fulfill all testing protocols were excluded from participation in the study.

Each participant underwent a comprehensive evaluation at two distinct temporal intervals: during the early menstrual phase (days 1–3 of menstruation) and seven days following menstruation, corresponding to the mid-follicular or ovulatory phase. At each assessment session, a meticulously structured test battery was administered in a systematic sequence. The evaluation commenced with the 22-item Menstrual Symptom Questionnaire (MSQ), which was specifically designed to evaluate physiological and psychological alterations associated with the menstrual cycle [14]. Each item was assessed using a 5-point Likert scale ranging from "never" to "always." This questionnaire was administered in a face-to-face format prior to the execution of any physical or vestibular testing.

Following this, the Timed Up and Go (TUG) Test was employed to evaluate dynamic balance and functional mobility. Each participant received instructions to rise from a seated position, traverse three meters, perform a turn, return, and subsequently sit down. The total duration required to complete the task was recorded in seconds.

The static and dynamic balance capabilities of participants were subsequently assessed through a series of structured postural control tasks, including: single-leg stance with eyes both open and closed, tandem stance, single-leg stance on a foam surface with eyes open and closed, and straight-line walking on a foam surface.

These tasks were specifically designed to evaluate postural control under conditions of altered visual and somatosensory input. Observational data were meticulously documented for each task to identify potential balance disturbances and compensatory strategies employed by participants.

After the balance assessments were finalized, VNG was carried out using the VisualEyes Spectrum system (Micromedical Technologies) to assess central oculomotor functions. The VNG protocol included evaluations of saccadic eye movements, smooth pursuit tracking, and optokinetic responses. These evaluations provided objective data concerning central visual-vestibular integration, independent of peripheral vestibular systems, and were analyzed in relation to established normative adult metrics. Following the central oculomotor evaluations, peripheral vestibular function was assessed in detail through the vHIT, targeting all semicircular canals. The Micromedical Interacoustic vHIT device recorded the parameters. A distance of 1 m was maintained between the subject's chair and the camera for measurements. The participants' head positions were fixed, and head impulses were performed bilaterally across the six semicircular canals. During lateral canal evaluation, participants were instructed to maintain gaze on a predetermined target without blinking. Subjects were advised against neck contraction and voluntary head movement. The chin was secured, and the lateral canal was aligned by tilting the head forward at 30°. Rapid head thrusts exceeding 150 degrees/sec were executed in the lateral plane at 15–20 degrees. A pause was observed after each head thrust to conclude the test. For vertical canal assessment, right anterior-left posterior and left anterior-right posterior canals were simultaneously evaluated. While maintaining gaze on the target, the head was rotated 35–45° to the respective side of the canal being tested. The procedure entailed stabilizing the chin with one hand and swiftly propelling the head in a vertical direction at velocities exceeding 150 degrees/sec, at an average inclination of 10–20 degrees.

In the final phase of each session, participants engaged in a virtual reality-based dual-task activity employing Beat Saber through the Sony PlayStation 4 VR. This rhythm-oriented game was selected to assess and enhance participants' postural stability, visuospatial coordination, and motor-cognitive integration within multitasking scenarios. In the immersive virtual reality context, each participant was equipped with a blue lightsaber in the right hand and a red lightsaber in the left hand. Participants were instructed to strike color-matched blocks (either blue or red) that approached them, adhering to the directional arrows displayed on the blocks. Concurrently, they were required to evade obstacles emerging from the front, left, or right, necessitating dynamic adjustments in posture. The exercise was supplemented by auditory stimuli (rhythmic music), enhancing attentional focus and motor planning. As participants successfully navigated sequences, the velocity and complexity of the game escalated, imposing greater demands on coordination and postural regulation. To ensure adherence to the task and appropriate challenge levels, the game implemented a performance threshold: a maximum of three errors (missed blocks or incorrect movements) was permissible per session. Surpassing this threshold resulted in automatic cessation of the game, and the final performance score was documented for subsequent analysis.

This arrangement aimed to engage cognitive domains such as attention and visuospatial processing while concurrently eliciting postural strategies, compensatory motor

Table 1 Descriptive statistics of participant demographics and menstrual characteristics

Variable	Mean (SD)	Median	Min–Max
Age	21.60 (1.79)	22.00	18.0–24.0
Menstrual Day	2.10 (0.79)	2.00	1.0–3.0
Menstrual Duration	28.75 (1.59)	28.50	26.0–32.0
Age at Menarche	13.40 (1.27)	13.00	11.0–16.0
Cycle Length (days)	5.70 (0.73)	6.00	5.0–7.0

(SD: Standard deviation; Min: Minimum; Max: Maximum)

responses, and locomotor control. Following the virtual reality session, participants completed the Cybersickness Questionnaire, which evaluated symptoms such as dizziness, nausea, fatigue, visual disturbances, and balance instability. Items were rated using a 10-point Likert-type scale, ranging from 0 (no symptoms at all) to 10 (symptoms experienced at an intolerable level), similar to the visual analogue scale (VAS) format.

Data analysis

All statistical analyses were carried out using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were computed to summarize the characteristics of the data, including median, minimum, maximum, and interquartile range values. Prior to hypothesis testing, the distribution of variables was evaluated using the Shapiro–Wilk test and visual inspection of histograms and Q–Q plots. Since most outcome variables did not meet the assumption of normality, non-parametric statistical procedures were applied in the subsequent analyses.

To examine differences between the menstrual phase and the post-menstrual phase, the Wilcoxon signed-rank test was employed for all paired comparisons, including vestibular and oculomotor outcomes, balance test performances, virtual reality task scores, and symptom ratings obtained from the MSQ and Cybersickness Questionnaire. A significance level of $p < .05$ was adopted for all analyses.

Results

A total of 20 participants were included in the analyses. Descriptive statistics regarding age, menstrual duration, and cycle characteristics are presented in Table 1. The mean age of participants was 21.60, with a mean menstrual duration of 28.75 days and an average cycle length of 5.70 days.

Vestibular and oculomotor test results obtained through saccade, smooth pursuit, optokinetic, and vHIT measurements are presented in Table 2. Mean values recorded during the menstrual and post-menstrual phases remained similar across all test types and frequencies. No statistically significant phase-related differences were observed in any of these measures.

Table 3 outlines the results of balance and functional performance tests across phases. Participants completed static and dynamic tasks including single-leg stance (with eyes open and closed), tandem stance, and foam-based walking. Among these, statistically significant improvements were observed in the post-menstrual phase for the Single Leg (Eyes Closed) condition ($p = .009$), the Single Leg

Table 2 Comparison of oculomotor and vHIT test results between menstrual and Post-Menstrual phases

Test	Freq./Side	Metric	Menstrual (Mean ± SD)	Post-Menstrual (Mean ± SD)	*P*-value (Wilcoxon)
Saccade	Left	LHl	171.55 ± 25.35	166.15 ± 24.21	0.433
Saccade	Left	LHr	175.75 ± 23.38	169.62 ± 21.73	0.109
Saccade	Right	RHl	168.35 ± 21.92	162.55 ± 19.44	0.351
Saccade	Right	RHr	171.25 ± 19.39	169.45 ± 18.91	0.866
Smooth Pursuit	0.1 Hz	LH	0.81 ± 0.09	0.83 ± 0.07	0.445
Smooth Pursuit	0.1 Hz	RH	0.82 ± 0.10	0.82 ± 0.07	0.984
Smooth Pursuit	0.2 Hz	LH	0.83 ± 0.11	0.89 ± 0.09	0.102
Smooth Pursuit	0.2 Hz	RH	0.82 ± 0.11	0.88 ± 0.09	0.051
Smooth Pursuit	0.4 Hz	LH	0.84 ± 0.10	0.89 ± 0.09	0.085
Smooth Pursuit	0.4 Hz	RH	0.81 ± 0.10	0.88 ± 0.08	0.058
Optokinetic	Left	LH	0.84 ± 0.10	0.88 ± 0.08	0.257
Optokinetic	Left	RH	0.84 ± 0.09	0.86 ± 0.07	0.513
Optokinetic	Right	LH	0.84 ± 0.08	0.88 ± 0.08	0.125
Optokinetic	Right	RH	0.86 ± 0.10	0.89 ± 0.09	0.235
vHIT	Horizontal	Gain	0.85 ± 0.04	0.85 ± 0.04	1.000
vHIT	LARP	Gain	0.83 ± 0.04	0.83 ± 0.04	0.833
vHIT	RALP	Gain	0.83 ± 0.04	0.82 ± 0.08	0.649

(LHl: Left Horizontal left; LHr: Left Horizontal right; RHl: Right Horizontal left; RHr: Right Horizontal right; LH: Left Horizontal; RH: Right Horizontal; LARP: Left Anterior–Right Posterior semicircular canal; RALP: Right Anterior–Left Posterior semicircular canal; vHIT: Video Head Impulse Test. SD: Standard deviation; Min: Minimum; Max: Maximum; EO: Eyes open; TUG: Timed Up and Go)

Table 3 Descriptive statistics of functional balance and performance tests across menstrual phases (EO: eyes open; SD: standard deviation; min: Minimum; max: Maximum; TUG: timed up and Go)

Test Name	Phase	Mean ± SD	Median	Min–Max	*P* value
Single Leg (EO)	Menstrual	11.70 ± 2.79	12.00	7–16	0.743
	Post-Menstrual	12.10 ± 2.45	12.00	7–17	
Single Leg (Eyes Closed)	Menstrual	7.00 ± 2.18	7.00	3–10	0.009
	Post-Menstrual	9.10 ± 2.27	9.50	5–13	
Tandem (Eyes Open)	Menstrual	9.45 ± 2.33	9.00	6–13	0.092
	Post-Menstrual	10.50 ± 2.84	10.00	6–15	
Single Leg Foam (EO)	Menstrual	6.15 ± 2.50	6.50	3–12	0.003
	Post-Menstrual	8.80 ± 2.76	9.00	5–16	
Walk on Foam	Menstrual	5.55 ± 1.82	5.00	2–9	0.034
	Post-Menstrual	6.75 ± 1.94	7.00	3–10	
Timed Up and Go (TUG)	Menstrual	7.37 ± 1.03	7.12	5.90–9.45	<0.001
	Post-Menstrual	7.15 ± 1.09	6.90	5.62–9.27	
Beat Saber Score	Menstrual	50.25 ± 18.67	55.00	10–82	<0.001
	Post-Menstrual	63.25 ± 16.98	63.00	28–90	

Foam (Eyes Open) task (p=.003), and the Walk on Foam test (p=.034). The Timed Up and Go test also yielded a significant decrease in completion time post-menstrually (p<.001). In the Beat Saber VR task, performance scores increased significantly after menstruation (p<.001). These phase-based differences are visualized in Fig. 1.

Figure 2 displays comparisons of five specific balance conditions: SL_EO, SL_EC, TANDEM_EO, SL_FOAM_EO, and WALK_FOAM. In all conditions, mean values in the post-menstrual phase were higher than those in the menstrual phase.

Responses from the MSQ are summarized in Table 4. Item-level scores varied, with several items standing out due to relatively higher mean values. Specifically, Q6 ("fatigue or tiredness") and Q14 ("bloating or swelling") had the highest average scores, each exceeding 3.00 on a 5-point scale. In contrast, items such as Q8 and Q11 reported lower means closer to 2.50. Median values across most items remained consistent, generally centered around 2.5 to 3.0.

Lastly, Cybersickness Questionnaire results following the VR session are shown in Table 5. Although not all differences reached statistical significance, post-menstrual scores were consistently lower across items. The most noticeable reductions were observed in Q5 ("nausea") and Q7S ("general discomfort"), where mean values decreased by more than one full point between phases. Similar trends were also present in Q4 and Q9, though with smaller differences.

Discussion

The present study aimed to examine the effects of hormonal fluctuations across the menstrual cycle on visual-vestibular integration and postural balance in healthy young women. Consistent with earlier work, we found that while low-level vestibulo-ocular functions remained largely unchanged across phases, functional balance, mobility, and

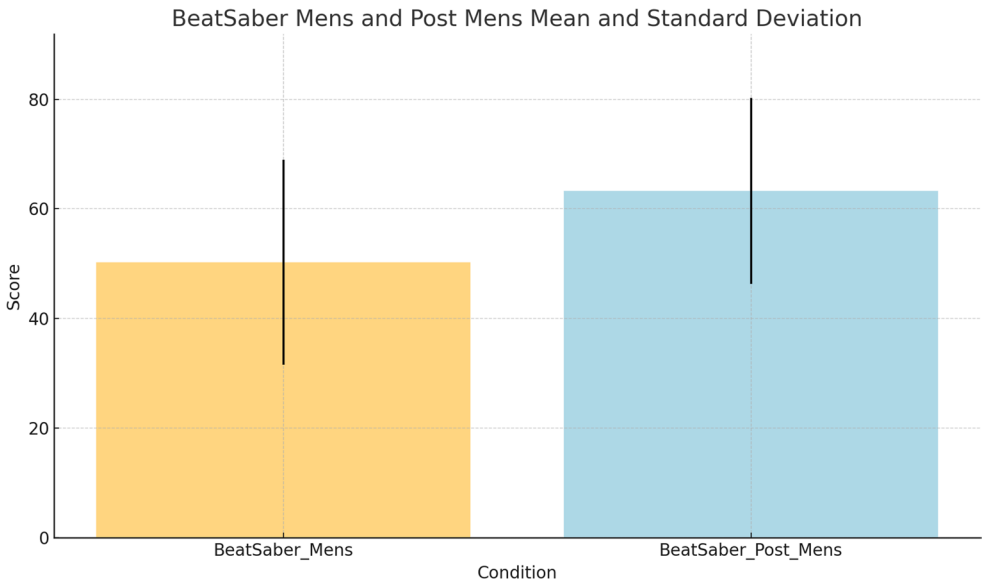


Fig. 1 Comparison of mean scores and standard deviations for the BeatSaber Mens (pre-test) and BeatSaber Mens Post (post-test) conditions. Error bars represent standard deviations. The post-test condition demonstrates a higher mean score, indicating a potential improvement following the intervention

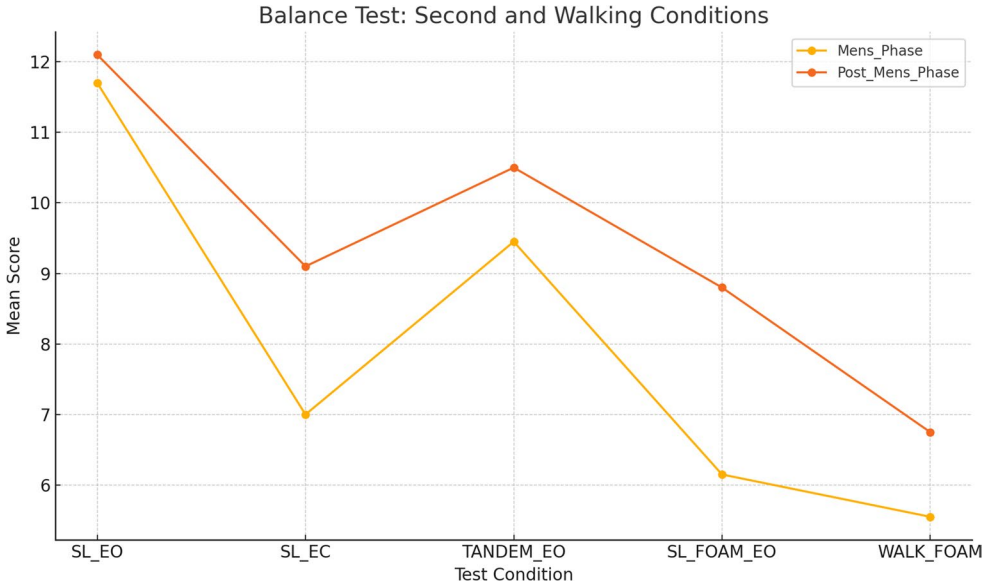


Fig. 2 Mean scores across five balance and walking conditions during the Mens_Phase and Post_Mens_Phase (post-intervention). The conditions include SL_EO, SL_EC, TANDEM_EO, SL_FOAM_EO, and WALK_FOAM. The plotted lines indicate changes in performance across phases, suggesting improvements in postural control and walking balance following the intervention

Table 4 Descriptive statistics for the 22 items of the MSQ

Question code	Mean (SD)	Median	Min - Max
Q1	2.60 (0.68)	3.0	1–4
Q2	2.90 (0.91)	3.0	1–4
Q3	2.80 (1.11)	2.5	1–5
Q4	2.60 (1.05)	2.0	1–5
Q5	2.70 (0.92)	2.5	2–5
Q6	3.30 (0.98)	3.0	2–5
Q7	2.85 (1.35)	3.0	1–5
Q8	2.75 (0.55)	3.0	2–4
Q9	2.65 (0.88)	2.0	2–5
Q10	2.95 (0.89)	3.0	1–4
Q11	2.65 (0.67)	3.0	2–4
Q12	2.80 (0.77)	3.0	2–4
Q13	2.65 (0.81)	2.0	2–4
Q14	3.40 (0.94)	3.0	2–5
Q15	2.85 (1.18)	3.0	1–5
Q16	2.80 (1.01)	3.0	1–5
Q17	2.90 (1.07)	2.5	2–5
Q18	2.85 (0.93)	3.0	1–4
Q19	2.65 (0.81)	2.5	2–5
Q20	3.05 (0.94)	3.0	1–5
Q21	2.50 (0.76)	3.0	1–4
Q22	2.95 (1.10)	3.0	1–5

(SD: standard deviation; min: Minimum; max: Maximum; Q1–Q22: items from the menstrual symptom questionnaire [MSQ])

motion-related discomfort significantly varied between the menstrual and post-menstrual phases.

VOR parameters assessed through vHIT, along with oculomotor functions including saccades, smooth pursuit, and optokinetic responses, did not exhibit statistically significant differences across menstrual phases in our study (Table 2). These findings are in parallel with previous research demonstrating that peripheral and brainstem-mediated vestibular pathways are largely unaffected by cyclical hormonal changes. Cengiz et al. [8] reported stable vHIT gains across phases in adolescents, while Sinha and Sahu [10] showed consistent VEMP and VOR responses throughout the cycle. Similarly, Mutlu et al. [15] found no significant phase-related differences in vHIT outcomes in healthy adult women.

In contrast, postural balance and functional mobility were significantly affected by menstrual phase. Notably, performance in the Single Leg Eyes Closed (p =.009), Single Leg Foam Eyes Open (p =.003), and Walk on Foam (p =.034) tests improved significantly in the post-menstrual phase (Table 3). These results are in line with prior findings highlighting balance deficits during hormonally active phases of the cycle. For instance, Baran and Yılmaz [4] found reduced sensory organization scores in women with dysmenorrhea during the early menstrual phase, suggesting that somatosensory and vestibular integration may be compromised when hormone levels are low or rapidly shifting. Similarly, Fridén et al. [9] reported increased postural sway and diminished proprioceptive acuity during the luteal and premenstrual phases, particularly in female athletes. Extending these findings, Kacem et al. [16] observed impairments in knee joint proprioception and postural control during premenstrual periods, supporting the view that neuromuscular coordination may be more vulnerable at specific cycle phases.

Improvements in dynamic mobility—reflected by faster Timed Up and Go (TUG) performance post-menstrually (p <.001)—are consistent with studies indicating phase-dependent changes in neuromuscular timing. For example, Lee and Yim [2] observed increased EMG activity in ankle stabilizers and greater postural sway around ovulation, attributing this to fluctuating estrogen levels affecting neuromotor control. Our findings further support that hormone-linked

Table 5 Phase-Based variation in cybersickness questionnaire responses

Question Code	Mens (Mean ± SD)	Post-Mens (Mean ± SD)	Mens Median	Post-Mens Median	Mens Min–Max	Post-Mens Min–Max
QS4	3.10 ± 2.10	2.15 ± 2.08	2.5	1.0	1–8	1–8
QS5	3.65 ± 2.21	2.05 ± 1.79	3.5	1.0	1–9	1–8
Q6S	2.35 ± 1.76	1.70 ± 1.75	2.0	1.0	1–7	1–8
Q7S	3.15 ± 2.37	1.95 ± 1.61	3.0	1.0	1–10	1–7
Q8	1.90 ± 2.27	1.15 ± 0.67	1.0	1.0	1–9	1–4
Q9	3.10 ± 2.51	1.85 ± 2.08	2.0	1.0	1–9	1–10
Q10S	1.55 ± 1.00	1.45 ± 1.00	1.0	1.0	1–4	1–5
Q11S	2.55 ± 2.04	1.75 ± 1.77	2.0	1.0	1–7	1–7
Q12S	1.55 ± 1.15	1.20 ± 0.70	1.0	1.0	1–5	1–4

(Mens: Menstrual phase; Post-Mens: Post-menstrual phase; SD: Standard deviation; Min: Minimum; Max: Maximum; QS/QS4–QS12: Items from the Cybersickness Questionnaire)

motor control modulation may extend to complex mobility tasks. Moreover, Piasecki et al. [17] emphasize that hormonal phase influences not only motor strength but also neural drive, potentially mediating the timing and efficiency of motor output in functional tasks.

The VR-based Beat Saber task introduced a novel way to examine multisensory and motor-cognitive integration. Participants achieved significantly higher scores in the post-menstrual phase (p <.001), aligning with evidence from Pohle et al. [12] that hormonal stability is associated with improved visuomotor performance. The observed phase-dependent improvement in VR task success is also supported by Ronca et al. [18], who reported that cognitive-motor performance improves post-menstrually due to stabilized hormonal influence on attention and executive function.

Furthermore, recent research indicates that hormonal status modulates susceptibility to cybersickness in VR settings. Apisa et al. [13] found that motion sickness symptoms were exacerbated during the luteal and menstrual phases, a pattern echoed in our findings, where nausea (Q5), general discomfort (Q7S), and headache (Q4) scores declined significantly post-menstrually (Table 5). These findings are in line with earlier reports by Matchock et al. [6] and Clemes and Howarth [19] who documented that sensory conflict adaptation is more challenging during phases with low estrogen levels, making females more vulnerable to visual-vestibular mismatch during menstruation. In support, Bannigan et al. [20] highlighted the role of hormonal modulation in neural excitability and sensory gating, suggesting a neurophysiological basis for the fluctuation in VR discomfort across the menstrual cycle.

In addition to menstrual cycle–related hormonal fluctuations, psychophysiological factors may also contribute to the variability of balance and cybersickness symptoms. For example, Kim et al. [21] reported that higher stress and negative affect were significantly associated with increased susceptibility to cybersickness in healthy adults, highlighting the role of psychological states in symptom perception. Similarly, Kourtesis et al. [22] demonstrated that individual traits, such as prior motion sickness history and gaming experience, are strong predictors of cybersickness severity, independent of hormonal influences. Moreover, poor sleep quality and baseline anxiety have been suggested as additional moderators of visual–vestibular conflict responses [23]. These findings indicate that the symptomatology observed in our study is likely the result of a multifactorial interaction, in which hormonal changes represent one, but not the only, contributing factor.

MSQ identified fatigue (Q6) and bloating (Q14) as the most frequently reported symptoms during menstruation (Table 4). Cybersickness scores were also notably reduced post-menstrually, which further supports the argument that sensory processing and integration may improve as hormonal stability increases.

Collectively, our findings reinforce the idea that hormonal fluctuations particularly around menstruation can impact not only balance but also the perception and tolerance of motion. These results are particularly relevant in light of growing clinical and occupational applications of VR, where gender-specific factors such as menstrual phase may influence performance and comfort.

This study contributes to the existing literature by integrating objective vestibular and oculomotor testing, functional balance assessments, immersive virtual reality exposure, and subjective symptom evaluations within a single experimental protocol. While previous research has typically examined menstrual cycle effects on balance using standard postural measures or hormonal estimations, few have incorporated detailed vestibular (vHIT) and oculomotor (saccade, pursuit, optokinetic) testing in tandem with behavioral tasks. Moreover, the inclusion of a VR-based dual-task condition followed by cybersickness assessment offers a novel lens into how menstrual phases may influence sensorimotor sensitivity under complex environmental demands. The combination of subjective and objective findings strengthens the ecological validity of the results and underscores the potential for menstrual cycle–based fluctuations to influence balance, visual-vestibular integration, and motion-related discomfort.

The occurrence of phase-related symptomatology in our participants has several clinical and methodological implications. Although oculomotor and vHIT measures remained stable across phases, differences in functional balance and dual-task performance, together with variability in self-reported MSQ and cybersickness symptoms, suggest that menstrual phase can influence visual–vestibular integration and mobility outcomes. This variability is not trivial: it indicates that assessment of balance, rehabilitation protocols, and task performance in women may differ depending on the phase of the menstrual cycle, and that unrecognized phase-related differences could confound interpretation in both clinical practice and research. To mitigate such effects, strategies including phase-aware scheduling of assessments, limiting initial task duration and incorporating scheduled breaks, graded exposure to challenging sensory conditions, and supportive vestibular or balance exercises may help reduce symptom burden. In addition, pre-session screening for factors such as prior motion sickness history, stress, or sleep quality could allow for individualized adjustments. These preventive approaches, while modest, may provide a pragmatic framework to minimize adverse responses and ensure more consistent outcome measurement.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, although menstrual cycle phases were identified based on participants' self-reported menstrual calendars and cycle regularity, no direct hormonal assays (e.g., serum estrogen or progesterone levels) were performed. Therefore, phase classification was based on structured self-report rather than biochemical verification. While this approach aligns with established methods in menstrual cycle research, the absence of hormonal measurement may have limited the precision of phase determination.

Second, despite employing a multimodal assessment protocol including vestibular, oculomotor, balance, and VR-based evaluations the study's cross-sectional design precludes examination of intra-individual fluctuations across the entire menstrual cycle. A longitudinal design could better capture temporal patterns in sensorimotor performance.

Finally, the inter-individual heterogeneity we observed in MSQ and cybersickness responses underlines that not all participants exhibited the same symptoms or severity; such variability is likely moderated by both hormonal and psychophysiological factors, and should be acknowledged when generalizing our findings.

In addition, while the VR dual-task served as a realistic sensorimotor challenge and was followed by symptom evaluation, real-time physiological responses (e.g., heart rate variability, center-of-pressure sway) were not measured during the task. Including such metrics in future studies could enhance the interpretation of postural and perceptual responses to immersive environments.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00405-025-09759-1.

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Author contributions Yuşa Başoğlu, PhD: Conceptualization, Methodology, Formal analysis, Supervision, Writing – Review & Editing. Sultan Çoban, BSc: Data curation, Investigation, Writing – Original Draft, Visualization, Project administration.

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Data availability The data supporting the findings of this study are available from the corresponding author, XXX, upon reasonable academic request. Requests for access to the anonymized datasets should be directed to [e-mail] and will be considered in accordance with institutional and ethical guidelines.

Declarations

Ethical approval This study was conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval was obtained from the *Istanbul Medipol University Non-Interventional Clinical Research Ethics Committee* (Decision No: 880; Date: 26.10.2023). All participants were informed in detail about the study's purpose, procedures, potential risks, and their right to withdraw at any time without penalty. Prior to data collection, each participant voluntarily signed a written Informed Consent Form.

Conflict of interest The authors declare that there are no conflicts of interest related to this work.

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