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A Comprehensive Evaluation of the Effects of Yoga-based Exercise on Vestibular Reflexes and Functional Balance

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ABSTRACT

Objective: To examine changes in saccular-mediated vestibulocollic responses, semicircular canal vestibulo-ocular reflex function, and static balance following an 8-week yoga-based exercise program in adults with prior irregular yoga experience, assessed using cervical vestibular-evoked myogenic potential (cVEMP), video head impulse test (vHIT), and the eyes-closed single-leg stance test (SLST).

Methods: This prospective, non-randomized comparative study initially enrolled 60 adults aged 20-45 years. The yoga group consisted of individuals with prior but irregular yoga experience; the controls had neither prior yoga experience nor regular participation in sports. Four yoga participants were excluded for not meeting the attendance criterion. The final sample included 26 yoga participants and 30 controls. The yoga group completed 24 standardized sessions over 8 weeks and underwent pre- and post-program assessments, whereas the control group was assessed once. Bilateral cVEMP responses, six-canal vHIT gains, and eyes-closed SLST times were assessed.

Results: The groups were comparable in age, sex distribution, and baseline vHIT and cVEMP parameters, although the baseline right-foot SLST differed between groups. In the yoga group, bilateral cVEMP amplitudes increased and eyes-closed SLST times for both feet improved (both $p<0.001$). vHIT gains did not change significantly. A nominal shortening in left cVEMP N1 latency ($p=0.011$) did not remain significant following Bonferroni correction. Bilateral within-group cVEMP amplitude changes remained significant after correction.

Conclusion: Following the 8-week yoga program, cVEMP amplitudes increased and eyes-closed single-leg stance times lengthened, whereas vHIT gains remained unchanged. These findings may be consistent with intervention-associated changes in saccular-origin vestibulocollic responses and static balance, but they do not establish a causal or direct physiological link between them.

Keywords: Vestibular evoked myogenic potentials, head impulse test, yoga, postural balance, vestibular function

INTRODUCTION

Yoga is a body of practices, originating thousands of years ago, that trains the body, the mind, and the breath together. These sequenced movement series, comprising physical postures (asana), breathing techniques (pranayama) and meditation (dhyana), are becoming increasingly widespread with the aims of reducing stress, increasing muscle strength and flexibility, supporting respiratory and cardiovascular function, and improving overall quality of life (1,2). The favorable effects of yoga on various conditions such as anxiety, depression, chronic pain and sleep disorders have been investigated with growing interest in recent years, and moderate evidence has been reported particularly for the reduction of depressive symptoms (3). It has been proposed that part of these effects may be related to the regulatory influence of slow, controlled breathing on the autonomic nervous system (4).

One of the notable effects of yoga is its contribution to postural control and balance. Balance is a multi-component function achieved through the central integration of inputs from the visual, proprioceptive and vestibular systems, and it contributes to the stabilization of both gaze and posture through the vestibulo-ocular reflex (VOR), vestibulospinal and vestibulocollic reflex (VCR) (5). Because yoga practice combines balancing postures that require standing on one leg, continuous readjustment of head and trunk in space, and attentive control of breathing, it has the potential to stimulate these systems. This potential is particularly evident for the vestibular system, which maintains balance and gaze stabilization during head movements. Indeed,

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the effects of yoga and similar mind-body exercises on balance and fall risk have been the subject of various studies in different age groups (6,7).

The relationship between yoga and balance has also been examined directly in previous studies. Baş Aslan and Livanelioğlu (8) demonstrated, using the flamingo balance test and the eyes-closed single-leg stance test (SLST), that six weeks of hatha yoga training significantly improved static balance in healthy young adults. Similarly, a systematic review of randomized controlled trials conducted in healthy individuals reported that the most consistent effect of yoga emerged on static balance, whereas its effects on fall frequency and fear of falling were variable (9). The finding that yoga-based exercise improves balance and mobility has also been supported by a randomized controlled trial in older adults (10) and by systematic reviews and meta-analyses (7,11). Although these findings point to a yoga-related gain in balance, the measurement methods employed have remained largely limited to examiner-dependent functional balance tests (11).

Although functional balance tests assess overall performance, they cannot isolate the contributions of visual, proprioceptive, and vestibular inputs. Objective measures allow a more focused assessment of vestibular pathways. The video head impulse test (vHIT) assesses the VOR during rapid head impulses in the planes of the semicircular canals (12-14). Vestibular-evoked myogenic potentials (VEMPs) assess vestibular reflex pathways associated with input from the otolith organs. Specifically, air-conducted cervical VEMP (cVEMP) predominantly reflects saccular-origin VCR responses recorded from the sternocleidomastoid (SCM) muscle (15-17), whereas ocular VEMP (oVEMP) provides complementary information about predominantly utricular-origin pathways. The present study administered cVEMP but not oVEMP; therefore, its otolith-related findings are limited to the saccular-mediated VCR response and cannot be generalized to utricular function.

The aim of the present study was to examine changes in six-canal vHIT gain, cVEMP measures, and eyes-closed static balance following an 8-week yoga-based exercise program in individuals with previous, but irregular, yoga experience, compared with a comparison group without previous yoga experience. This approach combines functional static balance assessment with objective evaluation of the semicircular canal VOR and predominantly saccularly mediated VCR responses.

METHODS

Ethics Approval

Approval was obtained from the Non-Interventional Scientific Research Ethics Committee of the Trakya University (decision number 03/40, decision date and: 27.02.2023). The study was conducted in accordance with the principles of the Declaration of Helsinki, and written informed consent was obtained from all participants before enrollment.

Study Design and Participants

This prospective, non-randomized comparative study initially enrolled 60 individuals aged 20-45 years. Participants were not randomly assigned to the study groups. Group membership was determined based on previous yoga experience. The yoga group initially consisted of 30 individuals who had previous, albeit irregular, yoga experience and participated in the active yoga exercise program. Four participants were excluded because they did not meet the predefined regular attendance criterion, leaving 26 in the yoga group for the final analysis. The control group consisted of 30 individuals with no previous yoga experience. Thus, the final analysis included 56 participants. The yoga group included 16 women and 10 men, whereas the control group included 20 women and 10 men. All participants were right-handed.

The yoga group was assessed twice, before participation in the exercise program and after its completion, whereas the control group was assessed once, in accordance with the study design, and served as the reference for comparison.

Inclusion and Exclusion Criteria

Individuals aged 20-45 years with right-hand dominance were eligible for participation. Eligibility was determined from the medical history obtained through a structured anamnesis. Participants were questioned about otological, neurological, and musculoskeletal conditions that could affect vestibular function or postural control.

Individuals with diagnosed vestibular disorders or a history of recurrent dizziness, neurological conditions affecting balance or coordination, or musculoskeletal disorders restricting postural control or exercise performance were excluded. Regular use of medications capable of affecting vestibular function, alertness, or postural stability was also an exclusion criterion.

Physical activity habits were assessed according to weekly exercise frequency, duration, and type. Group classification was based on previous yoga experience: the yoga group consisted of participants who had prior, non-regular yoga experience and were not practicing yoga at enrollment, whereas the control group consisted of individuals with no previous yoga experience and no regular participation in sports.

Sample Size Calculation

The sample size was calculated a priori using G*Power (version 3.1.9.7). Based on findings from comparable vestibular rehabilitation and multisensory balance-training studies (18,19), a large standardized effect size (Cohen's d=0.80) was specified for the power analysis. With an α error probability of 0.05 and statistical power (1-β) of 0.80, the analysis indicated that at least 27 participants were required per group. To account for potential attrition and data loss, the target sample size was increased to 30 participants per group. Accordingly, 60 participants were initially enrolled. Four participants in the yoga group were subsequently excluded because they did not meet the predefined regular

attendance criterion. Because the yoga intervention had already commenced as a fixed-cohort program, replacement recruitment was not feasible without introducing unequal intervention exposure. The final analysis, therefore, included 56 participants (yoga group, n=26; control group, n=30).

Yoga Exercise Programme

Participants completed a standardized program based on traditional yoga practice, incorporating asana (physical postures), pranayama (breathing techniques), and dhyana (meditation). The intervention comprised 24 sessions over 8 weeks (three 60-minute sessions per week). Each session included 35 minutes of asana, 15 minutes of pranayama, and 10 minutes of dhyana.

Asana (35 minutes). The first 5 minutes consisted of gentle stretching and joint mobilization. Standing postures included Tadasana (mountain pose), Vrikshasana (tree pose), Virabhadrasana II (warrior II), and Trikonasana (triangle pose), which were followed by Marjaryasana-Bitilasana (cat-cow pose) and seated Sukhasana (easy pose). Static postures were initially held for 15-20 seconds, progressing to approximately 30 seconds as tolerated, with two to three repetitions and brief rest intervals as needed. Wall or chair support was permitted initially during challenging balance postures and was gradually reduced. The asana component concluded with approximately 5 minutes of Shavasana (relaxation).

Pranayama (15 minutes). Participants performed diaphragmatic breathing, Nadi Shodhana (alternate-nostril breathing), and Bhramari (humming-bee breathing), each for 5 minutes. Breathing exercises were performed while seated, with slow, controlled respiration; forceful breath-holding and rapid-breathing maneuvers were avoided.

Dhyana (10 minutes). Seated comfortably, participants practiced breath-focused meditation with eyes closed or fixed on a stable point, emphasizing awareness of natural respiration, attentional focus, and relaxation.

Progression and safety. During weeks 1-2, emphasis was placed on learning the postures and adapting to the sequence. During weeks 3-5, posture-holding times were progressively increased; during weeks 6-8, participants practiced with greater control and independence. Intensity was individualized according to tolerance, and any posture associated with marked dizziness or postural instability was modified or discontinued.

Vestibular and Balance Assessment

The same standardized test battery and recording conditions were used for all assessments.

Video vHIT. The function of the VOR arc and the integrity of the semicircular canals were assessed using the Synapsys vHIT system (Inventis S.r.l., Padova, Italy). While the participant fixated on a stationary target in front of them, the head was passively moved with small-amplitude, rapid, and unpredictable impulses in the plane of each canal. Eye movements occurring during head motion were recorded with a high-speed video camera. The VOR gain was calculated for each of the six semicircular canals (right and left: anterior, posterior, and lateral), and the presence of covert and overt corrective saccades was evaluated. On the basis of normative values that are largely independent of age, healthy individuals with a VOR gain above 0.8 and without corrective saccades were included in the study (12,13).

cVEMPs VCR responses of predominantly saccular origin were assessed using cVEMP (Eclipse EP15, Interacoustics A/S, Middelfart, Denmark) (15,16). Participants were seated and instructed to turn their heads to the side contralateral to the stimulated ear to activate the ipsilateral SCM muscle. Recording electrodes were placed over the upper third of the SCM.

SCM activation was continuously monitored using the recording system's real-time surface electromyography (EMG) display. Tonic contraction was assessed using the root-mean-square (RMS) EMG amplitude, expressed in microvolts (μV). Recordings were obtained while SCM RMS activity was maintained within 50-150 μV. The difference between the right and left SCM RMS amplitudes was kept below 20 μV to minimize interaural contraction asymmetry. These criteria were checked during both PRE and POST recordings in the yoga group. The 20-μV asymmetry criterion was informed by Hançer Arslan et al. (20). No separate inferential comparison of SCM RMS values between visits was performed.

Air-conducted acoustic stimuli at 90 dB nHL were delivered, and short-latency myogenic responses were recorded from the ipsilateral SCM. For each ear, P1 (p13) and N1 (n23) latencies and P1-N1 peak-to-peak amplitude were measured (17,21). EMG amplitude normalization (EMG scaling) was not applied. This approach was informed by previous evidence that, when interaural SCM contraction differences are below 20 μV, EMG scaling does not significantly change the interaural cVEMP amplitude asymmetry ratio (20). Control of interaural asymmetry should not, however, be taken as proof of identical absolute SCM activation between visits.

Only individuals with identifiable bilateral P1/N1 responses at 90 dB nHL and an interaural cVEMP amplitude asymmetry ratio of 0.35 or less were included.

Eyes-closed SLST. The eyes-closed SLST was used to assess static balance ability (22). The participant was asked to stand with arms at the sides, lift one foot, and place the heel against the medial aspect of the knee of the contralateral leg. The stopwatch was started when the eyes were closed. The test was terminated if the position of the stance foot was disturbed, if heel-knee contact was lost, or if the eyes were opened. The test was repeated three times for each foot, and the mean of those trials was recorded as the stance time (seconds) for that foot.

Statistical Analysis

The normality of the distribution of each measurement variable was tested using the Shapiro-Wilk test, and homogeneity of variance for between-group comparisons was additionally

assessed using Levene's test. Demographic comparability between the yoga and control groups was assessed using the Mann-Whitney U test for age and the chi-square test for sex distribution. For paired-samples t-tests, the normality of within-participant differences was examined. Parametric tests (independent-samples or paired-samples t-tests) were applied to variables meeting the assumption of normality, and their non-parametric counterparts (Mann-Whitney U and Wilcoxon signed-rank tests) were applied to those that did not. The level of statistical significance was set at $p<0.05$, and the influence of multiple comparisons was evaluated with the Bonferroni correction ($\alpha\approx0.0014$). Analyses were performed with IBM SPSS Statistics 23.0 (IBM Corp., Armonk, NY, USA).

Variables analyzed with parametric tests are presented as mean ± standard deviation, whereas variables analyzed with non-parametric tests are presented as median and interquartile range (IQR; 25th-75th percentile).

RESULTS

The final analysis included 56 participants: 26 in the yoga group and 30 in the control group. The groups were comparable in terms of baseline demographic characteristics. Median age was 30.0 years (IQR: 24.0-32.8) in the yoga group and 28.5 years (IQR: 22.0-36.8) in the control group; there was no significant between-group difference (U=389.0, p=0.993). The yoga group included 16 women (61.5%) and 10 men (38.5%), whereas the control group included 20 women (66.7%) and 10 men (33.3). The sex distribution did not differ significantly between the groups (χ^2=0.160, p=0.690). All participants were right-hand dominant (Table 1).

Before the yoga exercise program, the yoga and control groups did not differ significantly on any of the measured objective vestibular test parameters (Table 2). Both vHIT gains and cVEMP latency and amplitude values were comparable between groups, indicating similar baseline vestibular function.

The most prominent pre-post differences were observed in cVEMP peak-to-peak amplitudes (Table 3). Amplitudes in both ears were higher after the program (both $p<0.001$). A shorter left-ear N1 latency was also observed at the nominal significance level (p=0.011), whereas right-ear N1 and bilateral P1 latencies did not change significantly. None of the six vHIT gains showed a statistically significant pre-post difference; the left lateral canal gain comparison yielded p=0.055.

In comparisons between the post-program yoga group and the single-assessment control group, left- and right-cVEMP amplitudes were higher in the yoga group ($p<0.001$ and p=0.006,

Table 1. Baseline demographic characteristics of the study groups

Variable	Yoga group (n=26)	Control group (n=30)	p
Age (years)	30.0 (24.0-32.8)	28.5 (22.0-36.8)	0.993[a]
Female, n (%)	16 (61.5)	20 (66.7)	0.690[b]
Male, n (%)	10 (38.5)	10 (33.3)	
Right-hand dominant, n (%)	26 (100)	30 (100)	-

Age is presented as median (IQR; 25th-75th percentile), and categorical variables as n (%). [a]Mann-Whitney U test, [b]Chi-square test, IQR: Interquartile range. Level of significance $p<0.05$

Table 2. Comparison of the yoga (PRE) and control groups at baseline

Variable	Yoga-PRE (n=26)	Control (n=30)	p
Right anterior canal gain	1.05 (1.00-1.08)	1.05 (1.02-1.07)	0.747[a]
Right posterior canal gain	1.02 (0.96-1.06)	1.02 (0.98-1.06)	0.980[a]
Right lateral canal gain	1.04±0.06	1.05±0.05	0.617[b]
Left anterior canal gain	1.07 (1.00-1.10)	1.07 (0.96-1.08)	0.424[a]
Left posterior canal gain	1.02 (0.96-1.06)	1.00 (0.96-1.06)	0.747[a]
Left lateral canal gain	1.02 (1.02-1.02)	1.05 (0.98-1.09)	0.418[a]
Left cVEMP P1 latency (ms)	12.95 (12.50-15.90)	13.30 (12.57-14.68)	0.615[a]
Left cVEMP N1 latency (ms)	25.04 (22.40-26.40)	25.39 (22.50-26.50)	0.303[a]
Left cVEMP amplitude (μV)	19.88 (19.11-26.05)	20.40 (19.40-22.75)	0.928[a]
Right cVEMP P1 latency (ms)	14.14±2.79	13.95±2.51	0.786[b]
Right cVEMP N1 latency (ms)	23.70 (20.19-26.19)	22.36 (20.91-25.68)	0.856[a]
Right cVEMP amplitude (μV)	28.40 (24.20-37.88)	25.60 (20.65-38.25)	0.464[a]

Values are given as mean ± standard deviation for parametric tests and as median (IQR; 25th-75th percentile) for non-parametric tests. [a]Mann-Whitney U test, [b]Independent samples t-test. Level of significance $p<0.05$. [c]VEMP: Cervical vestibular-evoked myogenic potential, N1: First negative wave, P1: First positive wave, vHIT: Video head impulse test, IQR: Interquartile range

respectively), and left-ear N1 latency was shorter (p=0.012) (Table 4). These comparisons should be considered in light of the non-randomized design and the absence of follow-up testing in the control group. Other cVEMP variables and all vHIT gains did not differ significantly between these groups.

The bilateral within-yoga-group cVEMP amplitude increases retained statistical significance after Bonferroni adjustment for 36 tests (α≈0.0014). The left-ear N1 latency finding (p=0.011) did not remain significant after correction and was therefore regarded as exploratory. The finding of left lateral canal gain (p=0.055) did not reach nominal statistical significance.

Eyes-closed SLST. In the yoga group, eyes-closed single-leg stance times were longer after the program for both feet (both p<0.001), which is consistent with improved performance on this measure of static balance (Table 5). At baseline, right-foot stance time was longer in the yoga group than in the control group (p<0.001), whereas the difference for the left foot was not significant (p=0.568). Post-program stance times for both feet were higher in the yoga group than in the single-assessment control group (both p<0.001). Because of a baseline right-foot difference, post-program between-group differences cannot be attributed solely to participation in the program.

DISCUSSION

The present study examined vHIT, cVEMP, and eyes-closed single-leg stance measures in adults with previous, irregular yoga experience, measured before and after an 8-week structured

Table 3. Comparison of pre-program (PRE) and post-program (POST) values in the yoga group

Variable	Yoga-PRE (n=26)	Yoga-POST (n=26)	p
Right anterior canal gain	1.05 (1.00-1.08)	1.05 (1.02-1.07)	0.483[c]
Right posterior canal gain	1.01±0.04	1.01±0.06	0.616[d]
Right lateral canal gain	1.04±0.06	1.06±0.05	0.269[d]
Left anterior canal gain	1.05±0.07	1.05±0.10	0.985[d]
Left posterior canal gain	1.02 (0.96-1.06)	1.00 (0.95-1.04)	0.889[c]
Left lateral canal gain	1.02 (1.02-1.02)	1.05 (0.98-1.09)	0.055[c]
Left cVEMP P1 latency (ms)	12.95 (12.50-15.90)	13.41 (12.80-14.68)	0.178[c]
Left cVEMP N1 latency (ms)	24.37±1.96	22.61±2.93	**0.011[d]**
Left cVEMP amplitude (μV)	24.4±10.6	30.1±8.7	**<0.001[d]**
Right cVEMP P1 latency (ms)	13.44 (12.14-15.30)	14.30 (13.05-14.80)	0.513[c]
Right cVEMP N1 latency (ms)	23.70 (20.19-26.19)	22.60 (20.96-25.68)	0.861[c]
Right cVEMP amplitude (μV)	31.0±8.4	36.0±6.9	**<0.001[d]**

Values are given as mean ± standard deviation for parametric tests and as median (IQR; 25th-75th percentile) for non-parametric tests. Significant results are shown in bold. [c]Wilcoxon signed-rank test, [d]Paired-samples t-test. Level of significance p<0.05. cVEMP: Cervical vestibular-evoked myogenic potential, N1: First negative wave, P1: First positive wave, IQR: Interquartile range

Table 4. Comparison of the yoga (POST) and control groups after the program

Variable	Yoga-POST (n=26)	Control (n=30)	p
Right anterior canal gain	1.05 (1.02-1.07)	1.05 (1.02-1.07)	0.823[a]
Right posterior canal gain	1.02 (0.98-1.06)	1.02 (0.98-1.06)	0.941[a]
Right lateral canal gain	1.06±0.05	1.05±0.05	0.695[b]
Left anterior canal gain	1.07 (0.96-1.08)	1.07 (0.96-1.08)	0.759[a]
Left posterior canal gain	1.00 (0.95-1.04)	1.00 (0.96-1.06)	0.684[a]
Left lateral canal gain	1.05 (0.98-1.09)	1.05 (0.98-1.09)	0.980[a]
Left cVEMP P1 latency (ms)	13.41 (12.80-14.68)	13.30 (12.57-14.68)	0.748[a]
Left cVEMP N1 latency (ms)	22.40 (20.54-24.50)	25.39 (22.50-26.50)	**0.012[a]**
Left cVEMP amplitude (μV)	30.20 (23.20-33.73)	20.40 (19.40-22.75)	**<0.001[a]**
Right cVEMP P1 latency (ms)	14.09±2.49	13.95±2.51	0.838[b]
Right cVEMP N1 latency (ms)	22.60 (20.96-25.68)	22.36 (20.91-25.68)	0.681[a]
Right cVEMP amplitude (μV)	34.60 (30.65-40.52)	25.60 (20.65-38.25)	**0.006[a]**

Values are given as mean ± standard deviation for parametric tests and as median (IQR; 25th-75th percentile) for non-parametric tests. Significant results are shown in bold. [a]Mann-Whitney U test, [b]Independent samples t-test. Level of significance p<0.05. cVEMP: Cervical vestibular-evoked myogenic potential, N1: First negative wave, P1: First positive wave, IQR: Interquartile range

Table 5. Eyes-closed single-leg stance: baseline, post-program, and paired comparisons (seconds)

Measurement	Control (n=30)	Yoga-PRE (n=26)	Yoga-POST (n=26)	p^1 baseline	p^2 paired	p^3 post
Right foot (s)	10.34 (9.36-11.24)	12.11±2.02	13.67±1.55	**<0.001**[a]	**<0.001**[d]	**<0.001**[a]
Left foot (s)	9.86±1.77	10.12±1.59	13.03±1.28	0.568[b]	**<0.001**[d]	**<0.001**[b]

For the right foot, control values are median (IQR; 25th-75th percentile), while yoga-PRE and yoga-POST values are mean ± standard deviation; all left-foot values are mean ± standard deviation. p^1: Yoga-PRE versus control, p^2: Paired yoga-PRE versus yoga-POST, p^3: Yoga-POST versus control. [a]Mann-Whitney U test, [b]Independent samples t-test, [d]Paired-samples t-test. Normality of the right-foot paired PRE-POST differences was supported (Shapiro-Wilk p=0.332), justifying the paired t-test in p^2. Significance threshold p<0.05; s: Seconds. IQR: Interquartile range

program. Bilateral cVEMP amplitudes and static single-leg stance times increased following the program, whereas six-canal vHIT gains did not change significantly. Between-group baseline measurements were comparable for vHIT and cVEMP, but right-foot SLST time at baseline was already higher in the yoga group. Thus, the observed pre–post differences are consistent with intervention-associated changes; the non-randomized groups and the lack of a repeated control assessment preclude firm causal attribution.

The differing patterns of cVEMP and vHIT findings should be interpreted at the level of measured reflex responses, rather than as direct evidence of selective improvement in the entire vestibular organ system. Air-conducted cVEMP predominantly reflects responsiveness of the saccular-origin VCR pathway, whereas vHIT assesses semicircular canal-mediated VOR function (12-17,23). Increased cVEMP amplitudes may be compatible with altered VCR responsiveness. However, absolute amplitudes are also influenced by tonic activation of the SCM, and monitoring EMG activity within predefined limits does not completely eliminate this influence. The nominal decrease in left-ear N1 latency did not survive multiple-comparison correction and should not be considered evidence of faster neural conduction. Aras et al. (24) reported no significant fHIT change after a single 30-minute hatha yoga session, while their computerized dynamic posturography findings differed according to the exercise condition. Their acute-session design differs substantially from our 8-week intervention, so any mechanistic parallels remain exploratory.

Previous investigations have commonly relied on functional balance outcomes. Baş Aslan and Livanelioğlu (8) used both the Flamingo Balance Test and the eyes-closed SLST to assess static balance in young adults following hatha yoga training. Our eyes-closed SLST measure is methodologically related to the latter assessment, although differences in protocols and training history limit direct numerical comparisons. Bajaj et al. (9) reviewed randomized studies using a range of balance-related outcome measures and reported relatively consistent findings for static balance, alongside more variable fall-related outcomes. These comparisons support the relevance of measuring static balance, but do not identify the sensory pathway responsible for any changes. In particular, coincident differences in SLST and cVEMP cannot be taken as evidence of a direct association without an appropriately specified correlation or mediation analysis.

Eyes-closed SLST time increased for both feet in the yoga group; however, this functional measure depends on multiple factors, including muscular strength, proprioception, attention, learning, and vestibular input. The observed SLST and cVEMP changes occurred during the same study period and may be considered parallel observations rather than evidence that the cVEMP change caused or explained the change in balance. Baseline right-foot SLST performance differed between groups, further complicating post-program group comparisons. Although all participants were right-hand dominant, lower-limb dominance was not measured; hand dominance cannot be used to infer preferred or supporting leg, and laterality-based explanations for the right-foot difference would be speculative (25-27).

A strength of this exploratory study is the combined use of six-canal vHIT, bilateral cVEMP, and eyes-closed SLST to describe different aspects of vestibular reflex function and static-balance performance. The within-group bilateral cVEMP amplitude changes remained significant after the specified multiple-comparison correction. Nevertheless, these recordings do not represent a comprehensive evaluation of otolith organ function because oVEMP was not obtained. The left N1 latency finding should be viewed as nominal and hypothesis-generating, rather than a confirmed physiological change.

Study Limitations

The study has several limitations. First, the groups were not randomized: the yoga group had prior, albeit irregular, yoga experience, while the control group had neither prior yoga experience nor regular participation in sports. Differences in prior exposure and activity habits could therefore have contributed to baseline performance and response to the intervention. The observed changes cannot distinguish the independent effect of the 8-week program from residual effects of prior yoga experience. Furthermore, controls underwent only one assessment, and thus time-related, test-retest, learning, and familiarization effects cannot be excluded.

Second, only cVEMP recordings were obtained; oVEMP recordings were not performed. Consequently, the results are limited to VCR responses of predominantly saccular origin, and no conclusions can be drawn regarding utricular or comprehensive otolith organ function. Although SCM RMS amplitudes were monitored and constrained during recordings, they were not formally compared between PRE and POST visits, nor was EMG amplitude normalization applied. Thus, differences in tonic SCM

activation may still have contributed to changes in absolute cVEMP amplitude. Screening was based on a structured medical history rather than a dedicated, comprehensive ophthalmological assessment.

Third, the eyes-closed SLST is a practical but nonspecific static-balance measure; it does not isolate vestibular contributions from proprioceptive, muscular, attentional, or practice-related influences. Dynamic balance, posturography, and lower-limb dominance were not assessed, and the control group had no repeated SLST measurements. The baseline right-foot difference should therefore be considered when interpreting group contrasts.

Finally, although enrollment met the planned target of 30 participants per group, four yoga participants failed to meet the attendance criterion and could not be replaced after the fixed-cohort program began, leaving 26 intervention participants for analysis. The relatively small sample precluded adequately powered, sex-stratified outcome analyses, and the findings should be replicated in larger studies with repeated control measurements and longer follow-up periods.

CONCLUSION

In participants with prior, but irregular, yoga experience, bilateral cVEMP amplitudes and eyes-closed single-leg stance times increased following the structured 8-week yoga-based program, while vHIT gains did not show statistically significant changes. These observations may be consistent with changes in VCR responsiveness of predominantly saccular origin and in static balance performance, but they do not establish a causal relationship between the two. Randomized studies incorporating repeated assessments in control participants, directly controlling SCM activation, including oVEMP recordings, and using more comprehensive balance measurements are needed. Whether long-term yoga practice might confer protection against later vestibular-related balance difficulties or falls remains to be tested in future longitudinal research.

Ethics

Ethics Committee Approval: Approval was obtained from the Non-Interventional Scientific Research Ethics Committee of the Trakya University (decision number 03/40, decision date and: 27.02.2023).

Informed Consent: Written informed consent was obtained from all individuals who participated in the study.

Footnotes

Author Contributions: Surgical and Medical Practices - G.H.A.; Concept - G.H.A., Ş.Y.; Design - G.H.A., Ş.Y.; Data Collection and/or Processing - G.H.A.; Analysis and/or Interpretation - G.H.A.; Literature Search - G.H.A., Ş.Y.; Writing - G.H.A., Ş.Y.

Conflict of Interest: The authors have no conflict of interest to declare.

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