

Article

Transforming Neurophysiology Through Stillness: A Randomized Controlled Study of Yoga Therapy in Autism Spectrum Disorder

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Abstract

Background: Autism Spectrum Disorder (ASD) involves social, emotional, and behavioral challenges, and conventional therapies show limited effectiveness. **Aims:** To evaluate the effect of Yoga Therapy (YT) on neurophysiological regulation and behavioral functioning in individuals with ASD. **Methods:** Thirty-six autistic individuals, aged 6 to 25 years and with Childhood Autism Rating Scale (CARS) scores above 15, were randomly assigned to yoga (YG) and control (CG) groups. YG received 60 min YT sessions twice weekly for six months alongside a regular school routine, while CG followed only a regular school routine. Handgrip strength (HGS), visual reaction time (VRT), systolic (SBP) and diastolic (DBP) blood pressure, heart rate (HR), and CARS scores were assessed at pre-, mid-, and post-intervention. Repeated measures ANOVA and Pearson's correlation were used for statistical analysis. **Results:** The study showed an increase in HGS ($\Delta = 3.27$ kg) and a reduction in VRT ($\Delta = -523.86$ ms) with a marked decrease in total CARS score ($\Delta = -5.67$), $p < 0.01$ in YG. There was a mild, non-significant reduction in cardiovascular (CV) dysfunction in YG, while CG showed no significant changes across all measures. **Conclusion:** Biweekly YT sessions over six months enhanced neurophysiological regulation, improving sensorimotor integration and accelerating cognitive, emotional, and behavioral outcomes in individuals with ASD.



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1. Introduction

ASD is a complex neurodevelopmental condition characterized by deficits in social communication, restricted interests, and repetitive behaviors. Beyond these core symptoms, individuals with ASD frequently experience comorbidities such as motor coordination difficulties, autonomic irregularities, and heightened CV risk [1,2]. Neuromuscular dysfunction manifests as poor grip strength, delayed sensorimotor integration, and impaired postural control [3], while autonomic dysregulation contributes to unstable blood pressure (BP),

irregular HR, and poor circulation [4]. These physiological challenges exacerbate behavioral difficulties, reduce adaptive functioning, and limit the effectiveness of conventional therapies, which often focus narrowly on cognitive or behavioral domains [5].

YT integrates physical postures, breath regulation, and relaxation techniques. Emerging evidence suggests that YT enhances neuromuscular coordination, improves sensory-motor integration, and modulates autonomic function [6–8]. Neurophysiological studies indicate that yoga practices can increase GABAergic activity, balance dopaminergic and serotonergic pathways, and strengthen prefrontal–limbic connectivity [9,10]. These mechanisms are directly relevant to ASD, where deficits in inhibitory control, attentional regulation, and emotional stability are prominent. By targeting both bottom-up autonomic recalibration and top-down cognitive modulation, YT addresses the biological underpinnings of ASD [11] rather than merely alleviating surface-level symptoms.

This study identified the following gap: only a limited number of trials have integrated objective neurophysiological markers—such as handgrip strength, reaction time, and CV parameters—with standardized behavioral assessments. Long-term investigations employing structured and reproducible YT protocols are rare, restricting clinical translation. The influence of YT on sensorimotor networks and autonomic regulation remains insufficiently examined, with minimal application of neuroimaging or electrophysiological techniques. Furthermore, most interventions prioritize behavioral outcomes, leaving CV and neuromuscular comorbidities insufficiently addressed.

This trial seeks to bridge these gaps by evaluating the impact of YT on neuromuscular function, sensorimotor integration, autonomic regulation, and behavioral outcomes in individuals with ASD. By combining clinical measures with neurophysiological markers, the study aims to provide evidence for YT as an innovative, multidimensional therapy that transforms neurophysiology through stillness, offering a pathway toward comprehensive care in ASD.

2. Materials and Methods

2.1. Trial Design and Setting

The study was conducted between September 2020 and May 2021, when the COVID-19 pandemic was still widespread, and knowledge and resources to manage the pandemic were limited. Nationwide lockdown and social distancing measures created major disruptions in daily life, making it especially difficult for the general public and healthcare workers to access essential services, including mental health support. This particular school conducted regular COVID-19 tests and informed parents that, if positive, the affected individual would be quarantined. None of the study participants tested positive. Despite these challenges, the study was successfully carried out in accordance with government guidelines, within the same school, where both groups experienced similar pandemic-related restrictions, thereby minimizing potential confounding effects. The purposive sampling method was employed for sample collection. Informed consent was obtained from all parents and school authorities for the participation of individuals with ASD in this study. The research adhered to CONSORT reporting guidelines [12] for the selection of outcome measures and analyses. The study was approved by the Institutional Human Ethical Committee of Aarupadai Veedu Medical College and Hospital [AV/IEC/2020/051] and was prospectively registered with the Clinical Trials Registry of India [CTRI/2021/12/038561]. This study explores the primary objective of the main study, investigating the therapeutic impact of yoga on neurophysiological functions that reduce autism severity in individuals with ASD. Prior publications have comprehensively covered the foundational aspects, including the background, literature review, pilot feasibility, modulation of neurotransmitters, and the innovative methods used in the research design.

2.2. Sample Size

The sample size was calculated using a sample size calculator for comparing two independent mean values ($\mu_1 = 83.50$; $\mu_2 = 89.55$) and standard deviations ($\sigma_1 = 6.0$; $\sigma_2 = 6.28$), derived from behavioral outcomes reported in a previous study [13]. With an assumed 80% statistical power and a 95% confidence interval, the required sample size was estimated at 34 participants. Factoring in a 5% anticipated dropout rate, the final required sample size was set at 36. It is relatively small and consistent with sample sizes used in similar randomized controlled trials in special school settings [13].

2.3. Participants

Forty-five individuals with ASD were screened, and thirty-six were recruited based on the criteria. Of the 36 participants, 14 were children (aged 6–12 years) and 18 adolescents (aged 13–18 years), while a smaller subset comprised 4 young adults (aged 19–25 years) who remained eligible for special school enrolment due to developmental delays. After randomization, two individuals over 18 years were included in each arm. This broad age range reflects the heterogeneous population typically served in special schools, ensuring ecological validity and capturing therapeutic effects across a representative developmental spectrum. Participants were included if they had a second-edition high-functioning Childhood Autism Rating Scale (CARS) score above 15 (covering mild to severe autism), had no prior exposure to yoga, and were able to perform yoga techniques with the aid of physical and verbal cues. Exclusion criteria involved difficulty comprehending yoga instructions even with assistance, the presence of acute medical, neurological, or co-morbid conditions such as eczema, uncontrolled asthma, and seizures, and the necessity for a caregiver. As a result, nine autistic individuals who did not meet the inclusion criteria were excluded, as given in Figure 1.

2.4. Randomization

Screening and recruitment were conducted prospectively, and randomization using a simple random number table, with each participant assigned to either “A” (YG) or “B” (CG) based on the sequence generated. This process ensured that each participant had an equal probability of assignment, and the final distribution resulted in 18 individuals per group. The allocation of participants into these two groups was carried out by the clerical staff of the specialized education school to avoid allocation bias.

2.5. Intervention

YG received 60 min YT sessions twice weekly (Tuesdays and Thursdays), integrated into their regular school routine for six months, while CG continued only with the regular school routine. YT sessions were held in a sensory-friendly hall at the specialized education school, assisted by three trained special educators. The environment was designed to promote relaxation and focus, using soft mats, calming colors, and minimal distractions. The investigator, a certified yoga therapist, also conducted the YT sessions. Full blinding was not feasible due to the nature of the intervention, though participants were partially blinded. Attendance was recorded, but eligibility was not contingent on attendance, as participation was voluntary.

2.6. YT Protocol

The YT protocol employed in this study was developed from prior pilot work and validated by subject experts to ensure reproducibility, as given in Table A1. All participants received the same structured sequence of practices—including jattis (dynamic balance postures), asana (breath-movement-coordinated postures), pranayama (breath regulation),

and relaxation techniques—delivered in 60 min sessions, twice weekly over six months. While the protocol was standardized, minor adaptations (e.g., additional verbal or physical cues) were permitted to accommodate individual differences in comprehension and motor ability, thereby ensuring inclusivity without altering the core sequence.

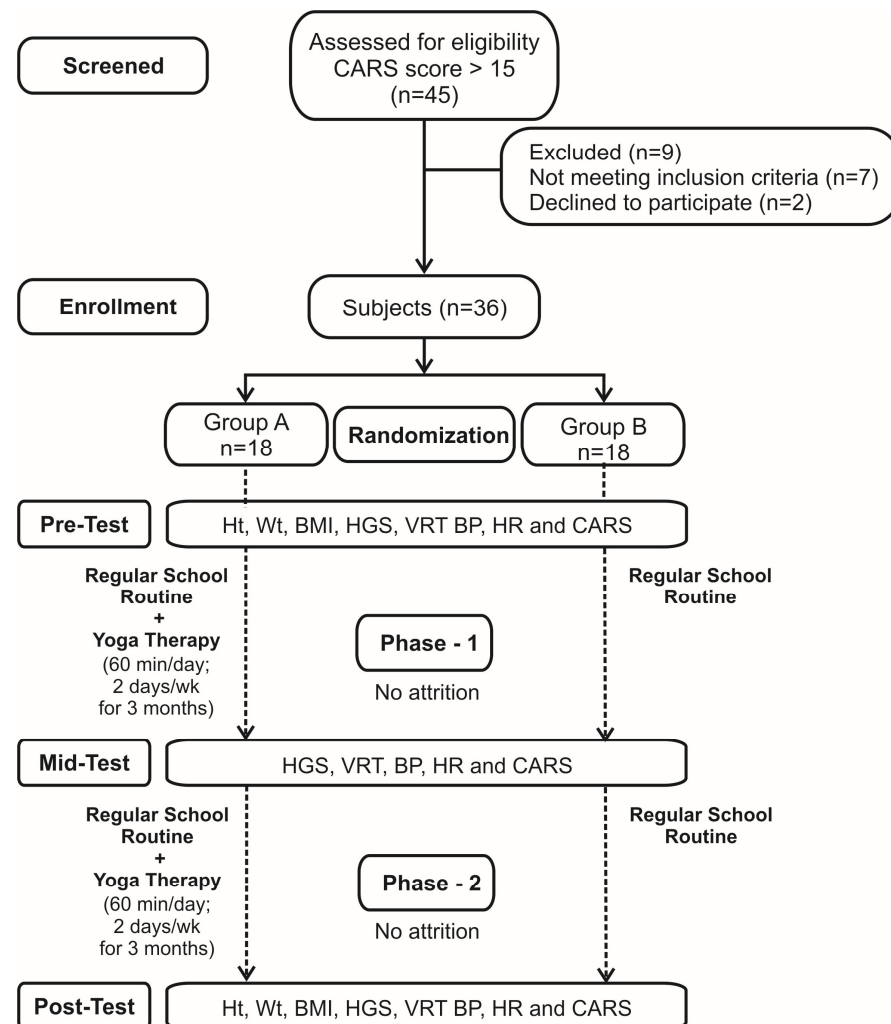


Figure 1. Effect of Yoga Therapy on reduction of ASD symptoms—participants’ flow diagram.

2.7. Measurement Tools

Two trained special education teachers conducted pre- (1st month), mid- (4th month), and post- (7th month) assessments of demographic, anthropometric, neuromuscular, and CV variables, and autism severity. Height and weight were measured using standardized digital tools, including the CROWN PRESTIGE height measuring stadiometer and the Boldfit digital weighing machine, India. HGS and VRT were assessed using a Camry digital hand-grip dynamometer and a validated digital reaction time apparatus (Anand Agencies, Pune, India), administered by trained special education teachers. Participants were instructed to exert maximal voluntary force with their dominant hand, and HGS values were recorded in kilograms to reflect neuromuscular function and motor coordination. VRT was designed to capture the latency between visual stimulus presentation and motor response. Assessments were conducted under controlled conditions by blinded evaluators, ensuring reliability and minimizing detection bias. BP and HR were recorded using an, Omron HEM 7124, OMRON Healthcare India PVT Ltd., Haryana, India. Autism severity was measured using CARS, administered by a clinical psychologist under the supervision of a psychiatrist, minimizing detection bias. The data collectors were blinded throughout the study.

2.8. Data Analysis

Data were analyzed using SPSS (version 16.0), applying descriptive statistics, correlation, repeated measures ANOVA, Post hoc comparison with Bonferroni adjustment, and effect size (Cohen's *d*). Analyses were performed at significance levels of $p < 0.05$, 0.01, and 0.001, with 95% confidence intervals.

3. Results

The demographic, anthropometric, and autism severity variables of the subjects, that is, age, gender, height, and weight, and autism severity, were comparable at the baseline as determined by Student's *t*-test and Chi-square test. Additionally, there was no significant mean difference in the pre-intervention measures of HGS, VRT, SBP, DBP, and HR between the two groups, ensuring no risk of selection bias, as given in Tables 1 and 2. The study showed no significant difference in the mean values of post intervention data of height, weight, and BMI in individuals with ASD.

Table 1. Baseline comparison of demographic and anthropometric variables, as well as autism severity between groups using Chi-square test and Student's *t*-test.

Variables	Yoga (n = 18)	Control (n = 18)	<i>p</i> Value
Gender			
Male	16	14	0.367 *
Female	2	4	
Age (yr)	13.28 ± 05.23	12.33 ± 04.65	0.571
Height (cm)	149.50 ± 23.93	145.28 ± 19.03	0.562
Weight (kg)	43.03 ± 20.33	43.59 ± 16.64	0.929
BMI	18.10 ± 04.84	19.93 ± 04.43	0.244
Autism severity	50.33 ± 04.75	50.86 ± 04.82	0.743

* Fisher's exact test.

In Table 2, RM-ANOVA between-group effects with partial eta squared (η^2), Bonferroni-adjusted post hoc within-group comparisons across time (pre, mid, and post), and standardized within-group change magnitudes using Cohen's *d* based on pooled standard deviations of the two timepoints were compared.

Participants in YG showed significant improvements in HGS ($\Delta = 4.74$, $p < 0.001$; $d_{av} \approx 1.31$), nearly doubling their scores, while CG ($\Delta = 0.62$, not significant; $d = 0.24$) showed only minor changes. VRT also improved markedly in YG ($\Delta = -542.11$, $p < 0.01$; $d = -0.93$), indicating enhanced sensorimotor function, whereas CG ($\Delta = +395.22$, not significant; $d = +0.53$) experienced a slight decline. Although both groups showed increases in SBP (YG, $\Delta = +35.50$, $p < 0.001$; $d = 1.39$; CG, $\Delta = +11.39$, $p < 0.05$; $d = 0.72$) and DBP (YG, $\Delta = +18.56$, $p < 0.001$; $d = 1.34$; CG, $\Delta = +18.17$, $p < 0.001$; $d = 1.11$) over time, there were no significant differences between them. HR remained largely unchanged across both groups (YG, $\Delta = +4.22$; CG, $\Delta = +1.33$).

Most notably, autism severity as measured by CARS scores decreased substantially in YG ($\Delta = -10.56$, $p < 0.001$; $d = -1.85$), with no meaningful change in CG ($\Delta = -0.22$, not significant; $d = -0.11$), highlighting the potential of YT to positively impact core symptoms of ASD. Adjusted analysis showed significant differences between yoga and control groups in HGS ($\eta^2 = 0.210$), VRT ($\eta^2 = 0.233$), and CARS ($\eta^2 = 0.259$).

Table 2. Comparative analysis of neurophysiological and behavioral outcomes between and within groups using RM-ANOVA.

Variables	Times	Yoga (n = 18)	Control (n = 18)	Between (YG-CG)	F Value	p Value	Cohen's d
HGS	Pre	4.52 ± 2.10	3.98 ± 2.19	3.274 \$\$	9.036	0.005	0.210
	Mid	8.94 ± 7.20 #	4.32 ± 2.42				
	Post	9.26 ± 4.67 ##	4.60 ± 2.93				
	(I – J)	4.74 ###	0.62				
	F value	8.215	1.417				
	p value	0.001	0.284				
VRT	Pre	1339.61 ± 760.34	1529.83 ± 765.21	−523.86 \$\$	10.356	0.003	0.233
	Mid	1279.76 ± 543.76	1533.56 ± 706.21				
	Post	797.50 ± 323.16 ##	1925.06 ± 713.48				
	(I – J)	−542.11 ##	395.22				
	F value	8.505	2.422				
	p value	0.005	0.097				
SBP	Pre	100.83 ± 12.43	110.06 ± 25.59	−2.852	0.184	0.671	0.005
	Mid	106.22 ± 15.56	120.44 ± 22.69				
	Post	136.33 ± 41.24 ###	121.44 ± 23.49 #				
	(I – J)	35.50 ###	11.39 #				
	F value	12.430	3.889				
	p value	0.003	0.051				
DBP	Pre	59.17 ± 11.63	63.00 ± 23.26	−5.148	1.069	0.308	0.030
	Mid	68.50 ± 15.47 #	76.67 ± 16.41 #				
	Post	77.72 ± 18.76 ###	81.17 ± 17.14 ###				
	(I – J)	18.56 ###	18.17 ###				
	F value	14.623	11.491				
	p value	0.001	0.001				
HR	Pre	83.89 ± 11.33	94.17 ± 16.57	−7.148	3.260	0.080	0.087
	Mid	94.17 ± 10.66 #	97.94 ± 21.15				
	Post	88.11 ± 9.61	95.50 ± 12.87				
	(I – J)	4.22	1.33				
	F value	6.048	0.611				
	p value	0.483	1.000				
CARS Score	Pre	50.33 ± 4.75	50.86 ± 4.82	−5.67 \$\$	11.861	0.002	0.259
	Mid	45.08 ± 5.69 ###	50.69 ± 4.52				
	Post	39.78 ± 6.73 ###	50.64 ± 4.90				
	(I – J)	−10.56 ###	−0.22				
	F value	58.439	0.105				
	p value	0.001	0.920				

$p < 0.05$, ## $p < 0.01$, and ### $p < 0.001$ delineate significant mean values within groups; \$\$ $p < 0.01$ delineate significant mean values between groups using RM-ANOVA. HGS: handgrip strength; VRT: visual reaction time; SBP: systolic blood pressure; DBP: diastolic blood pressure; HR: heart rate; CARS: Childhood Autism Rating Scale; I – J: post-pre.

4. Discussion

4.1. Impact of YT on Neurophysiological Modulation

YT produces systemic effects through both bottom-up autonomic pathways and top-down neurocognitive modulation [14].

4.1.1. Enhancement of Neuromuscular Function: Cortical Drive and Proximal Stabilization

YT produced a substantially greater improvement in HGS ($\Delta = 3.27$ kg, $p < 0.01$) than control, with a large within-group increase ($\Delta = 4.74$ kg, $p < 0.001$), as shown in Table 2 and Figure 2a,b.

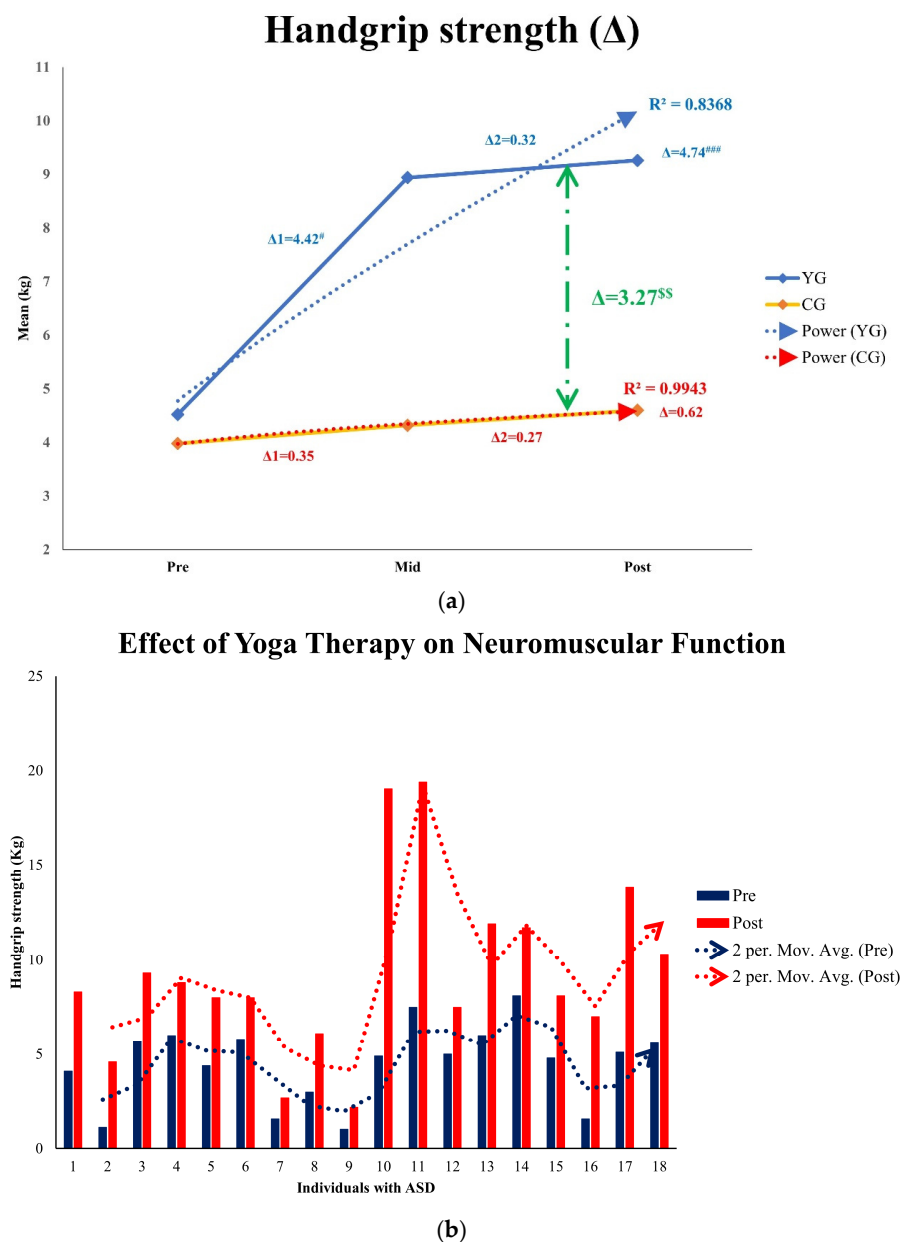


Figure 2. (a): Comparison of delta value of HGS both within and between groups. (b): Comparison of pre- and post-assessment values of HGS among individuals with ASD in YG.

This improvement reflects that yoga postures and sustained isometric practices quickly enhance corticospinal excitability, motor unit recruitment, and proprioceptive acuity, leading to measurable increases in grip strength within weeks. These changes are largely peripheral and neuromuscular, explaining their earlier manifestation [15], and reflect enhanced central motor drive and improved neuromuscular coordination [15]. Joshi et al. (2017)

demonstrated that yoga improves nerve–muscle physiology and motor coordination in occupational groups, consistent with evidence that grip strength responds rapidly to repetitive motor training due to improved central motor drive [16]. Breath-synchronized movement may further refine motor unit recruitment, while yoga practices enhance proprioceptive acuity and sensorimotor integration, thereby improving voluntary force output [14,17–20]. Additionally, regulated breathing techniques help balance sympathetic–parasympathetic pathways and promote GABAergic modulation, supporting inhibitory control and emotional regulation [21–23]. Dopaminergic activation during motor engagement enhances motivation and reward processing [24], whereas serotonergic shifts contribute to mood stabilization and cognitive development [25–27].

4.1.2. VRT: Sensory-Motor Processing and Attentional Efficiency

YT led to a clinically meaningful speeding of reaction time by a significant reduction in VRT ($\Delta = -523.86$ ms, $p < 0.01$) compared to CG, with a large within-group reduction ($\Delta = -542.11$ ms, $p < 0.01$), as illustrated in Table 2 and Figure 3a,b.

Improvements in VRT require longer exposure because they involve higher-order processes such as prefrontal activation, sensory–motor integration, GABAergic modulation, and dopaminergic transmission. These cortical and neurotransmitter changes evolve more gradually, supporting attentional efficiency and executive control [28–30]. This substantial reduction in VRT, consistent with improved sensory–motor integration and faster central processing, enhances attentional networks and executive function, likely via increased prefrontal activation and reduced limbic interference [31–33]. Pranayama techniques further enhance prefrontal activation, facilitating faster stimulus processing and executive control [34]. These practices also stimulate dopamine transmission, which enhances attention, motivation, and goal-directed behavior through modulation of prefrontal cortical activity [32,33]. Additionally, elevated GABA levels—shown to increase by 27% following a 60 min yoga session [31,35,36]—contribute to improved inhibitory control and sensory filtering by regulating neuronal excitability and synchronizing cortical networks [37–39]. Furthermore, serotonergic modulation supports emotional regulation and improves interoceptive awareness and adaptive responses, contributing to refined motor precision and cognitive development [40].

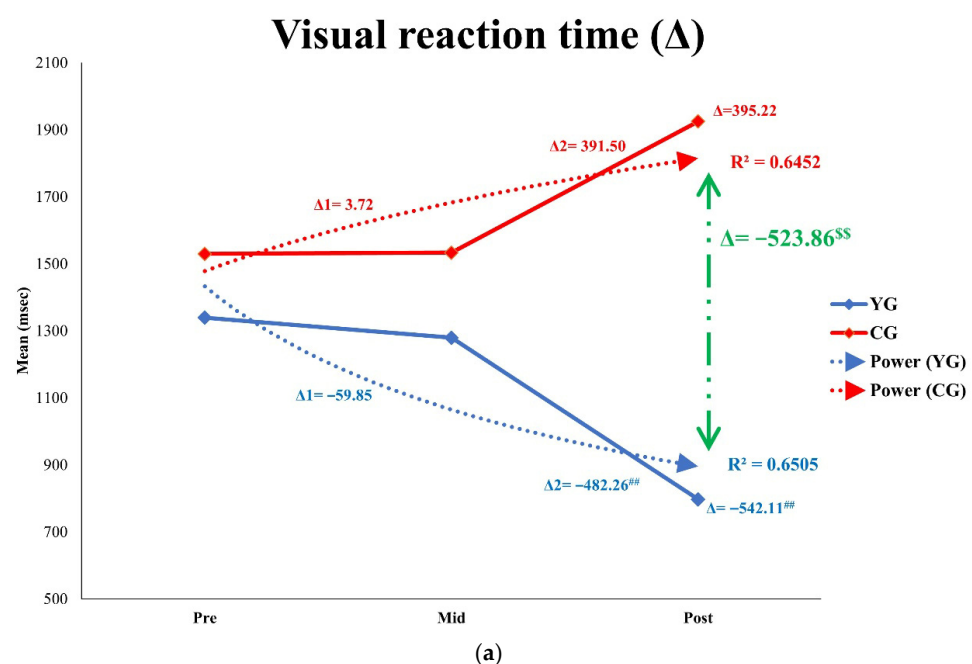


Figure 3. Cont.

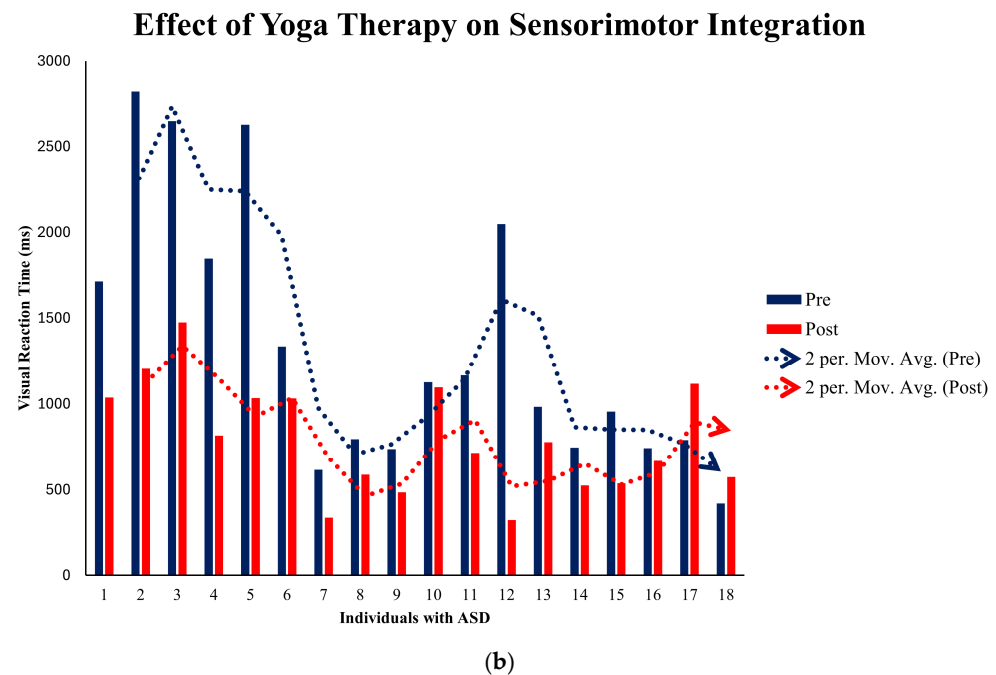


Figure 3. (a): Comparison of delta value of VRT both within and between groups. (b): Comparison of pre- and post-assessment values of VRT among individuals with ASD in YG.

Consistent with these mechanisms, Shobana et al. (2021) found that yoga training significantly reduced VRT in young adults, but changes were more pronounced after sustained practice [28]; Chatterjee et al. (2021) reported that yoga improves audiovisual reaction times by enhancing sensory–motor association and cortical processing [41]; and Voss et al. (2023) highlighted that short-term yoga has limited impact, while longer practice improves sensory integration and reaction speed [42].

4.2. Impact of YT on CV Function

SBP, DBP, and HR showed intra-group variations over time but did not differ significantly between the yoga and control groups. This suggests that while YT may bring about modest autonomic effects [43,44], the protocol employed in this study was not sufficient to produce clinically significant CV changes within the six-month timeframe [45,46]. Several factors may explain this outcome: (i) the relatively small sample size, which limited statistical power for detecting subtle autonomic shifts; (ii) the heterogeneity of participants in terms of age and autism severity, which may have influenced CV responsiveness; and (iii) the focus of the YT protocol on neuromuscular and behavioral regulation rather than intensive CV training.

Clinically, these findings indicate that YT, as implemented in this study, primarily benefits neuromuscular and behavioral domains, while CV modulation remains limited. Although SBP increased within the YG, this rise reflects normal intragroup variation and neuromuscular engagement rather than anxiety, as evidenced by the absence of significant intergroup differences and the concurrent improvements in behavioral outcomes. Prior studies have shown that yoga enhances corticospinal excitability, proprioceptive acuity, and sensorimotor integration, leading to early neuromuscular gains [47,48], while CV recalibration in ASD populations often requires longer duration, higher frequency, or pranayama-dominant protocols to achieve clinically meaningful autonomic shifts [30,49,50]. Thus, the observed SBP changes should be interpreted as benign physiological adaptation rather than adverse stress response, reinforcing that the primary therapeutic impact of yoga in this context lies in neuromuscular strengthening and behavioral regulation.

4.3. Impact of YT on Reduction in Autism Severity

YT produced a significant reduction in CARS score ($\Delta = -5.67$, $p < 0.01$) compared to CG, with a large within-group reduction ($\Delta = -10.56$, $p < 0.001$), as illustrated in Table 2 and Figure 4a,b. This improvement can be attributed to enhanced neuronal plasticity in regions such as the cerebellum and sensorimotor cortex [51,52]. These effects are mediated by neurotransmitter shifts: increased GABA improves motor planning and inhibitory control [53], elevated serotonin supports emotional regulation, and balanced dopamine enhances executive functioning and cognitive flexibility [54]. This modulation of neurotransmitters in neural circuits can be involved in emotion regulation, attention, and social cognition. Several studies suggest that yoga enhances prefrontal–limbic connectivity and reduces amygdala hyperactivity, which may improve behavioral flexibility and reduce stereotypical behavior [14].

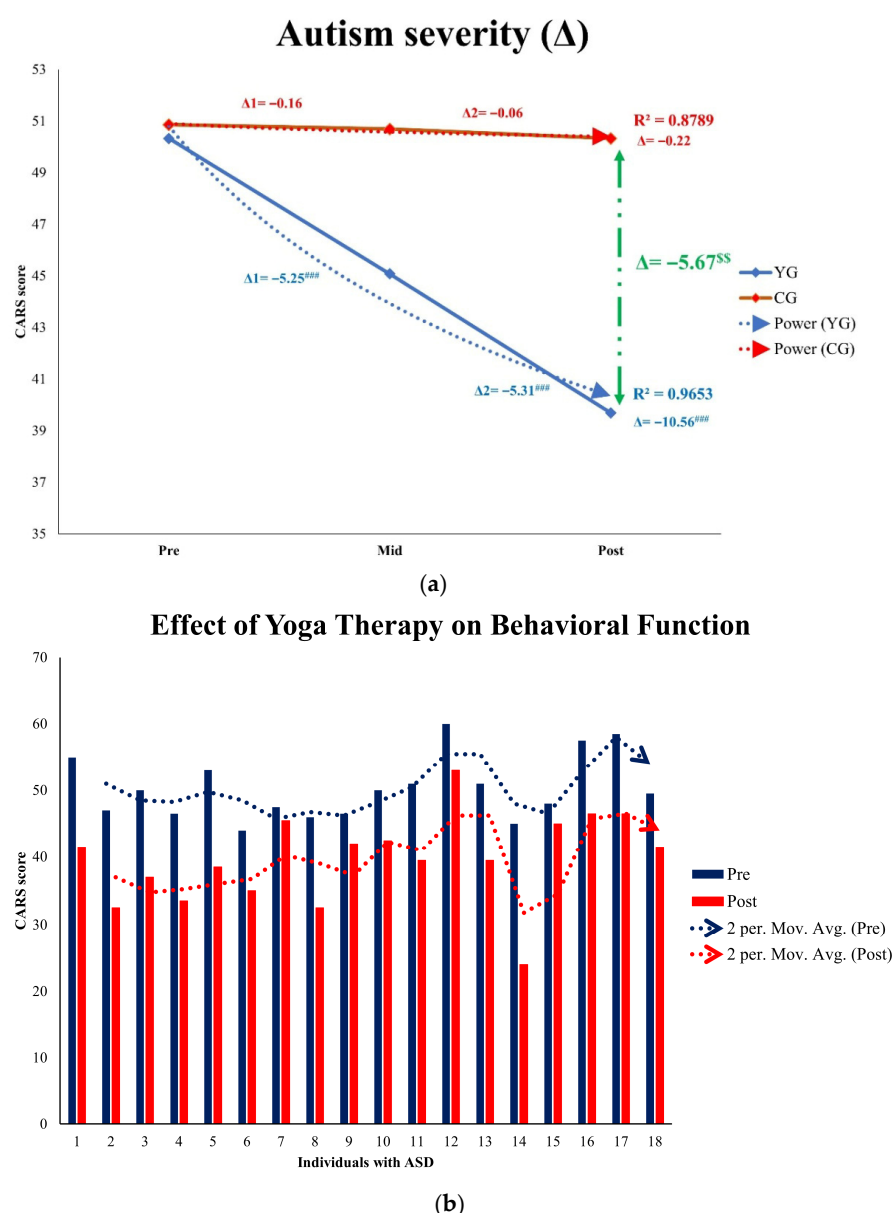


Figure 4. (a): Comparison of delta value of CARS score both within and between groups. (b): Comparison of pre- and post-assessment values of CARS score among individuals with ASD in YG.

4.4. Association of Neurophysiological Function with Behavioral Improvements

4.4.1. Neuromuscular Function vs. Autism Severity

Figure 5 illustrates an inverse relationship ($r = -0.540$, $p < 0.001$) between increased HGS ($\Delta = 3.27$ kg) and reduced CARS score ($\Delta = -5.67$) in autistic individuals, which can be attributed to enhanced neuromuscular function and sensory-motor integration [55].

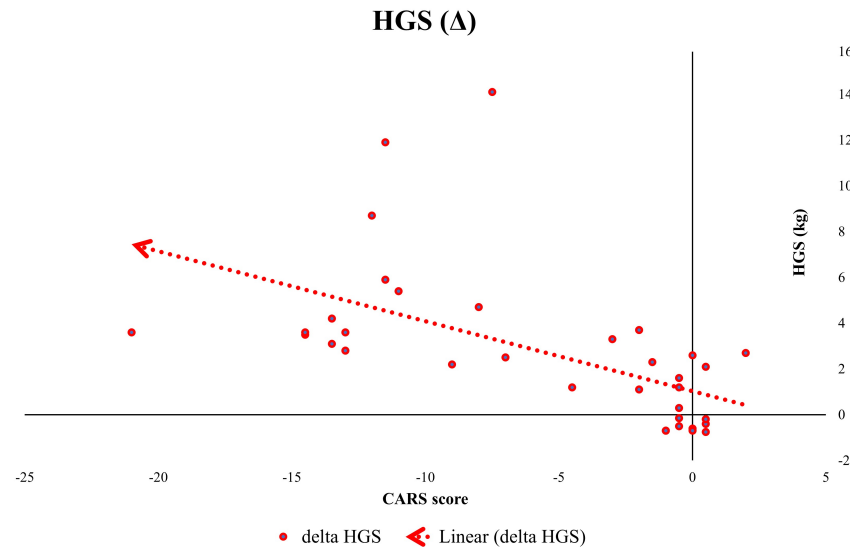


Figure 5. Negative correlation between delta value of HGS and CARS score.

Improved HGS has been associated with enhanced microstructural integrity in sensorimotor-related white matter pathways, including the corticospinal and proprioceptive tracts [56]. These neural pathways are critical for motor coordination and executive function—domains often impaired in ASD. Moreover, fractional anisotropy in the brain-stem’s corticospinal tract has been found to predict both HGS and ASD symptom severity. This suggests that improvements in HGS may reflect enhanced neuroplasticity and integration between cortical and subcortical motor regions, promoting better behavioral regulation and reduced ASD symptom severity [52,57–60].

4.4.2. Sensory–Motor Integration vs. Autism Severity

Figure 6 illustrates a significant positive correlation ($r = 0.535$, $p < 0.001$) between reduced VRT ($\Delta = -523.86$ ms) and decreased CARS score ($\Delta = -5.67$) in individuals with ASD. Faster VRT reflects improved sensory processing and attentional control [61], linked to magnocellular pathway activation essential for detecting dynamic social cues [62]. Reduced VRT facilitates engagement of cortical–subcortical regions (e.g., amygdala, prefrontal cortex) involved in social cognition [62]. Due to increased sensory sensitivity and elevated neural activity in the visual cortex among individuals with ASD, strategies that enhance visual processing speed may help alleviate symptom severity by fostering more effective sensory integration, sharper attentional control, and greater behavioral adaptability essential for social engagement [63]. These findings support the hypothesis that faster visual processing facilitates better integration of sensory input, leading to improved behavioral regulation and reduced autism severity [64].

The moderate correlations ($r \approx \pm 0.5$) between HGS and autism severity, and between VRT and autism severity, indicate that improvements in neuromuscular strength and sensory-motor integration contribute meaningfully to behavioral change, but are not sole determinants. These biomarkers act as part of a broader neurophysiological network, suggesting that YT exerts multidirectional effects where motor and attentional gains synergize with neurotransmitter modulation and cortical connectivity to reduce autism severity.

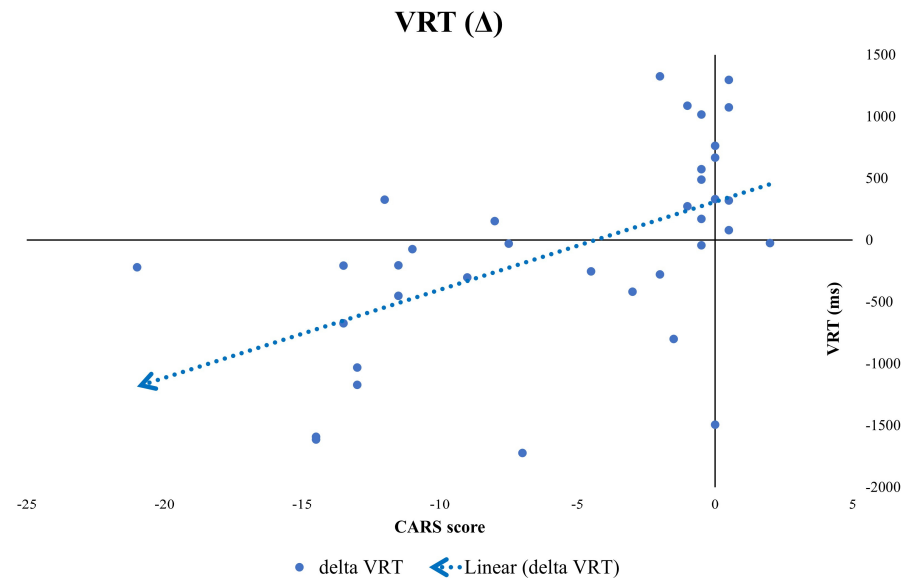


Figure 6. Positive correlation between delta value of VRT and CARS score.

4.5. Accelerated Impact of YT on Neurophysiological and Behavioral Functions

In Figure 4a, the reduction in CARS score observed in YG ($\Delta = -10.56$, $p < 0.001$) not only reached statistical significance but also exceeded the threshold generally considered clinically meaningful in prior ASD intervention studies, where a reduction of ≥ 4 –5 points has been associated with observable improvements in social communication and behavioral functioning [65]. In contrast, CG showed only a minimal change ($\Delta = -0.22$), indicating that YT facilitated behavioral progress at a rate nearly 10 times faster. This rapid and clinically relevant improvement is attributed to multidirectional neurophysiological modulation, alongside the interactive group setting that fostered engagement, peer modeling, and social reciprocity despite baseline challenges linked to social isolation.

4.6. Risk of Bias Analysis

Risk of bias was minimized through allocation concealment, unbiased randomization, standardized outcome measurement, controlled attrition, and impartial data collection and reporting. Lifestyle factors such as diet, physical activity, and medication use could have influenced the outcomes. To minimize these confounders, participants were recruited from the same specialized school setting, where daily routines, dietary provisions, and physical activity schedules were relatively uniform. Parents and teachers confirmed that participants did not engage in extracurricular activity outside of school during the study period, and no new medications were initiated during the intervention. The dual role of investigator and therapist may increase the risk of performance bias. To mitigate this, participant effort during yoga sessions was monitored using the Assessment of Yoga Performance Ability©. The overall quality of the study was rated as “low risk”. The average effect size (Cohen’s $d = 0.3$) suggests a small to moderate impact, reinforcing the therapeutic potential benefits of yoga for individuals with ASD [66]. Hence, YT promotes neuroplasticity and emotional regulation, reinforcing its therapeutic value in ASD.

4.7. Generalizability Impact of YT on Neurophysiological Mechanism

The study allowed us to capture the real-world heterogeneity of the school population. However, this subgroup could introduce potential bias, particularly in terms of developmental stage and functional capacity. This diversity is a strength of the study, as it reflects the heterogeneous developmental spectrum typically served in special schools and demonstrates that YT can be feasibly applied across childhood, adolescence, and young

adulthood. Importantly, the improvements observed in HGS, VRT, and reductions in CARS scores were consistent across age groups, underscoring the therapeutic impact of yoga on both neurophysiological and behavioral outcomes. The gains in HGS and VRT suggest enhanced sensorimotor integration and cognitive processing, likely mediated by top-down mechanisms such as increased mindfulness and interoception. Meanwhile, changes in SBP and DBP reflect bottom-up autonomic shifts, possibly reducing hyperarousal and sensory overload—common challenges in ASD (Table A2). The significant reduction in CARS scores correlates with these physiological changes, supporting the hypothesis that neurophysiological regulation through YT can lead to behavioral improvements. This aligns with the biopsychosocial model, where physiological stability fosters emotional and behavioral regulation.

Primary outcomes directly measured were HGS, VRT, CV parameters, and CARS scores. Statements regarding neurotransmitter modulation and cortical connectivity are interpretative in nature and indirectly supported by the present data. These references were included to situate our findings within the broader neurophysiological literature on YT and autism.

5. Limitations

Limitations and their potential impact on the study, and possible strategies to overcome them, are as follows:

- (a) Heterogeneity of participants (age, autism severity, and psychological categories): This diversity may have introduced variability in responsiveness to YT, limiting the precision of conclusions. Future studies should stratify participants by age bands and severity levels or employ larger samples to allow subgroup analyses.
- (b) Preponderance of males aged 13–25 years: This gender imbalance, partly due to COVID-19 restrictions and school dropout among females, may reduce generalizability. Strategies to overcome this include targeted recruitment of female participants and multi-site studies to ensure balanced representation.
- (c) Small sample size: The limited number of participants reduces statistical power and increases the risk of type II error. Larger, multi-center randomized controlled trials are needed to confirm these findings and enhance external validity.
- (d) Absence of complete blinding (investigator was also the therapist): This may have introduced performance bias. Future studies should employ independent therapists and blinded assessors to minimize bias.
- (e) Use of CARS as the sole measure of autism severity: While CARS is validated and feasible, it may not capture the full spectrum of behavioral and neurocognitive changes. Future research should integrate complementary scales such as ADOS-2 and Vineland Adaptive Behavior Scales to strengthen clinical interpretation.
- (f) Lifestyle factors: Individual variations in diet and physical activity were not systematically monitored, which limits the ability to fully attribute observed changes to YT alone. Future studies should incorporate dietary records and physical activity logs to better control for these potential confounders and strengthen causal inference.
- (g) Parallel controlled group design: The observed effects may or may not be replicated in the absence of the structured school routine, since YT was implemented here as a supplement to daily activities. An alternative design could be participants undergoing an initial six-month phase without YT, followed by a six-month intervention phase. Such within-subject data would arguably provide stronger evidence by accounting for interindividual variability more effectively than the current parallel-group design.

These limitations provide a transparent account of how each factor may have influenced the study outcomes and outline practical strategies to improve methodology in subsequent trials.

6. Conclusions

Biweekly YT sessions over a six-month period showed significant neurophysiological benefits for individuals with ASD, improving HGS and VRT, and reducing autism symptom severity. These improvements reflect enhanced neuromuscular coordination, sensory–motor integration, and neurotransmitter modulation. While CV effects remain modest, the observed SBP rise reflects benign physiological adaptation rather than anxiety; at the same time, the therapy demonstrated substantial impact on cognitive and behavioral functions, with accelerated improvements linked to increased neuroplasticity and cortical activation. Overall, YT emerges as an evidence-based intervention, promoting integrated motor, emotional, and social development in individuals with ASD. Further research is needed to assess the long-term effects of YT with a larger sample size, its scalability, and the specific elements of yoga that contribute most significantly to improvements in these areas.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Human Ethical Committee of Aarupadai Veedu Medical College and Hospital (Protocol code: AV/IEC/2020/051, Approval Date: 25 July 2020) and was prospectively registered with the Clinical Trials Registry of India (CTRI/2021/12/038561).

Informed Consent Statement: Written informed consent has been obtained from all parents and school authorities for the participation of individuals with ASD in the study.

Data Availability Statement: The data presented in this study are available on request.

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Abbreviations

The following abbreviations are used in this manuscript:

ASD	Autism spectrum disorder
CARS	Childhood autism rating scale
CG	Control group
CV	Cardiovascular

DBP	Diastolic blood pressure
EEG	Electroencephalogram
GABA	Gamma-aminobutyric acid
HGS	Handgrip strength
HR	Heart rate
HRV	Heart rate variability
RM-ANOVA	Repeated measures analysis of variance
SBP	Systolic blood pressure
SPSS	Statistical Package for Social Sciences
VRT	Visual reaction time
YG	Yoga group
YT	Yoga therapy

Appendix A

Table A1. Yoga Therapy protocol.

S. No.	Yoga Practice *	Procedure	Holding (Counts)	Repetition (Round)	Duration (min)
Play way jattis					
1	Right leg forward and backward	A basic warm-up routine for rehabilitation, incorporating gentle, oscillatory movements in a back-and-forth pattern to promote mobility and engagement in a playful manner.	10	3	3
2	Left leg forward and backward		10	3	3
Asana					
3	Tadasana	The subject stands on the toes with both hands hooked and outstretched above the head.	10	3	3
4	Vrkshasana	The subject stands on one leg with the opposite knee bent, both hands clasped and extended above the head.	10	3	3
5	Padahastasana	The subject bends forward from a standing position, with variations that involve grasping the toes.	10	3	3
6	Paschimottanasana	The subject sits with legs extended forward, bending from the hips to stretch the entire back of the body, including the spine, hamstrings, and shoulders.	10	3	3
7	Pawanamuktasana	The subject lies on their back and draws both knees toward the chest, a position that may help release trapped gas, alleviate constipation and indigestion, and stimulate the digestive system.	10	3	3
8	Jathara parivrttasana	The subject lies on their back with one knee drawn across the body toward the opposite side of the chest.	10	3	3

Table A1. Cont.

S. No.	Yoga Practice *	Procedure	Holding (Counts)	Repetition (Round)	Duration (min)
9	Bhujangasana	In a prone position, the subject inhales while lifting the chest and head, keeping the hips grounded.	10	3	3
10	Sarvangasana	In a supine position, the subject inhales while lifting the legs, hips, and back off the mat, bringing the legs perpendicular to the floor.	10	3	3
Pranayama (in Padmasana/Sukhasana)					
11	Adham Pranayama	The subject breathes deeply into the abdomen, expanding it during inhalation and contracting it during exhalation, while producing the sound “aaa...”.		3	3
12	Madhyam Pranayama	The subject breathes deeply into the mid-lung area, expanding it during inhalation and contracting it during exhalation, while producing the sound “uuu...”.		3	3
13	Adhyam Pranayama	The subject breathes deeply into the upper-lung area, expanding it during inhalation and contracting it during exhalation, while producing the sound “mmm...”.		3	3
14	Pranava Pranayama	The subject breathes deeply into the lower chest, expanding it during inhalation and contracting it during exhalation, while producing the combined sound “aaaauummm...”.		3	3
Relaxation					
15	Shavasana	In a supine position, the subject lies flat on the back with arms and legs extended, palms facing upward, and eyes closed.			>3
Total duration					60

**/ Subject to individual's ability regarding physical and verbal cues.

Table A2. Impact of Yoga Therapy on integrative neurophysiological mechanism.

Dependent Variables	Integrative Neurophysiological Mechanism
Handgrip Strength	- Yoga promotes biomechanical and neurochemical processes to facilitate better motor performance and enhanced cortical activation. - Cortical motor drive, proprioception, and trunk stability. - Increased α-EEG power and reduced θ-EEG activity post-yoga suggest heightened cortical readiness and attentional control—key for isometric effort.

Table A2. Cont.

Dependent Variables	Integrative Neurophysiological Mechanism
Visual Reaction Time	- Yoga enhances thalamo-cortical connectivity and reduces sympathetic tone, which may accelerate stimulus-response coupling. - Optimizing sensory responsiveness and cognitive-motor performance.
Blood Pressure and Heart Rate	- Yoga reduces sympathetic outflow and improves vagal modulation, which stabilizes BP over time. The lack of differential effect in the study may be due to baseline normotension or short intervention duration. - While Yoga Therapy supports overall autonomic balance and neurochemical signaling, its impact on CV dysfunction in ASD appears nuanced and modest, involving mechanisms beyond direct cardiac stimulation. - Breath-regulated vagal afferents modulate brainstem autonomic centers, reducing HR variability and promoting CV efficiency.
Autism severity	- Yoga enhances mindfulness and awareness of internal bodily sensations (interoception), which in turn improves self-regulation through top-down brain mechanisms. - Meanwhile, bottom-up shifts in the autonomic nervous system help reduce hyperarousal and alleviate sensory overload.

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