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Effectiveness of Multimodal Ergonomic Interventions Versus Standard Postural Education for Smartphone-Related Postural Dysfunction: A Three-Arm Randomized Controlled Trial

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Abstract

Background: Smartphone-related postural dysfunction (SRPD), encompassing forward head posture (FHP), thoracic kyphosis, and rounded shoulder deformity, has emerged as a significant musculoskeletal public health concern. While postural education is widely used, it lacks the environmental and behavioral specificity required for durable correction in habitual smartphone users.

Objective: To evaluate and compare the effectiveness of three interventions — Multimodal Ergonomic Intervention (MEI), Wearable Posture Biofeedback Training (WPBT), and Standard Postural Education (SPE) — on postural parameters, pain, disability, and behavioral smartphone habits in adults with SRPD.

Design: Three-arm, parallel-group, assessor-blinded Randomized Controlled Trial (RCT).

Setting: Physiotherapy Outpatient and Occupational Health Department, Tamil Nadu, India.

Participants: 120 adults aged 18-40 years with clinically confirmed SRPD and habitual smartphone use ≥5 hours/day.

Interventions: Group A (MEI, n=40): workstation/device ergonomic restructuring + targeted exercise + behavioral modification. Group B (WPBT, n=40): real-time posture biofeedback via wearable sensor + corrective exercise. Group C (SPE, n=40): structured postural education sessions (active control). Duration: 8 weeks.

Outcome Measures: Primary — Craniovertebral Angle (CVA) via photogrammetry; Thoracic Kyphosis Index (TKI). Secondary — VAS, NDI, Rounded Shoulder Angle (RSA), Smartphone Addiction Scale-Short Version (SAS-SV), and adherence rates.

Results: Group A (MEI) demonstrated the greatest improvement in CVA (9.4° improvement, $p<0.001$) and long-term behavioral outcomes (SAS-SV reduction: 34.2%). Group B (WPBT) showed superior short-term postural correction adherence (82.4%) and VAS pain reduction (52.8%). Group C (SPE) showed statistically significant but clinically modest improvements across all domains. No serious adverse events were recorded.

Conclusion: Multimodal ergonomic intervention produces the most comprehensive and durable outcomes for smartphone-related postural dysfunction. Wearable biofeedback adds significant value for real-time compliance monitoring. An integrated MEI-WPBT protocol is recommended for clinical practice and workplace health programs.

Keywords: Smartphone Ergonomics, Postural Correction, Forward Head Posture, Wearable Biofeedback, Text Neck, Thoracic Kyphosis, Randomized Controlled Trial, Physiotherapy, Behavioral Intervention, Craniovertebral Angle

Introduction

The integration of smartphones into virtually every domain of modern life has fundamentally altered human postural behavior. Unlike traditional ergonomic hazards that are confined to occupational settings, smartphone-related postural dysfunction (SRPD) pervades all environments — domestic, educational, occupational, and recreational — for extended durations throughout the day. The habitual adoption of the 'smartphone posture' — characterized by forward head posture (FHP), thoracic hyperkyphosis, and bilateral rounded shoulder deformity — imposes cumulative biomechanical stress on the cervical and thoracic spines and the shoulder girdle complex.

The craniovertebral angle (CVA) has been established as a reliable, valid, and clinically accessible measure of forward head posture. A CVA below 50 degrees is considered indicative of clinically significant FHP [14]. Epidemiological data indicate that among habitual smartphone users, mean CVA values of 44–47 degrees are frequently observed, reflecting a population-level shift toward pathological head-forward positioning [1, 8].

Despite the well-documented postural consequences of smartphone use, current physiotherapy management protocols for SRPD remain heterogeneous and largely reactive. Three primary intervention paradigms have been employed: (1) Standard Postural Education (SPE), wherein patients receive structured instruction regarding optimal posture and device-use habits — a widely accessible but behaviourally insufficiently potent intervention; (2) Wearable Posture Biofeedback Training (WPBT), in which real-time postural deviations are detected by inertial measurement unit (IMU) or electrogoniometric wearable sensors and corrected through vibrotactile or auditory feedback, leveraging operant conditioning principles; and (3) Multimodal Ergonomic Intervention (MEI), a comprehensive approach integrating environmental ergonomic restructuring, targeted therapeutic exercise, and behavioral habit modification strategies derived from behavioral science frameworks including the Transtheoretical Model and Implementation Intentions Theory.

The relative efficacy of these three approaches has not been rigorously compared within a single, well-powered RCT. The present study was designed to fill this important evidence gap, with the additional goal of establishing a clinically actionable, hierarchy-of-evidence-based protocol for the physiotherapeutic management of SRPD in the contemporary Indian and global clinical context.

CONSORT Compliance Statement

This trial was designed, conducted, and reported in full compliance with the CONSORT 2010 Statement for parallel-group RCTs [11]. The CONSORT flow diagram and checklist are appended as supplementary materials. The trial protocol was registered prospectively in the Clinical Trials Registry of India (CTRI) prior to participant enrollment.

Aims and Objectives

- To compare the effects of Multimodal Ergonomic Intervention (MEI), Wearable Posture Biofeedback Training (WPBT), and Standard Postural Education (SPE) on craniovertebral angle (CVA) in adults with SRPD.
- To evaluate the impact of each intervention on thoracic kyphosis index (TKI), rounded shoulder angle (RSA), and cervical range of motion.
- To assess pain (VAS) and functional disability (NDI, QuickDASH) outcomes across the three arms.
- To determine the effect of each intervention on smartphone use behavior (SAS-SV, daily usage duration).
- To evaluate treatment adherence, participant satisfaction, and safety across the three interventional groups.
- To identify predictors of treatment response for personalized ergonomic intervention planning.

Review of Literature

Epidemiology and Biomechanics of Smartphone-Related Postural Dysfunction

The prevalence of neck pain among smartphone users ranges from 64% to 89% in cross-sectional studies, with significantly higher rates observed in populations using smartphones for more than 4 hours daily [13]. The biomechanical mechanism is straightforward but consequential: the neutral head position imposes approximately 4.5–5.4 kg of force on the cervical spine; at 15°, 30°, 45°, and 60° of forward flexion, this increases to 12, 18, 22, and 27 kg respectively — a sixfold amplification at maximum flexion [5]. The prolonged application of these compressive and shear forces induces posterior cervical muscle fatigue, intervertebral disc loading asymmetry, ligamentous creep, and progressive loss of cervical lordosis.

Thoracic kyphosis associated with smartphone use is compounded by the adoption of a slumped sitting posture, which reduces lumbar lordosis and generates a compensatory increase in thoracic kyphosis — the so-called 'smartphone spine' deformity. Straker L et al. (2009) demonstrated that every 10° increase in thoracic kyphosis was associated with a 14% increase in neck extensor muscle activation, creating a pathological biomechanical feedback loop perpetuating pain and postural distortion.

Standard Postural Education

Standard postural education (SPE) — delivered through verbal instruction, visual aids, and printed materials regarding optimal smartphone use posture — has demonstrated short-term efficacy in improving postural awareness and transient CVA improvements [14]. However, behavioral science evidence consistently indicates that knowledge provision alone produces minimal durable behavior change [10]. The lack of real-time corrective feedback and absence of environmental modification limits SPE's effectiveness as a standalone intervention for chronic SRPD.

Wearable Posture Biofeedback Training

Wearable posture biofeedback devices utilizing IMU sensors (accelerometer-gyroscope arrays) detect sagittal-plane postural deviations in real time and deliver vibrotactile alerts when defined threshold deviations are exceeded. This approach exploits the neurophysiological mechanism of operant conditioning — the vibrotactile alert functions as an aversive stimulus contingent on postural lapse, reinforcing corrective postural behavior through negative reinforcement. Caneiro et al. (2013) demonstrated that 4 weeks of biofeedback device use significantly reduced forward head posture (CVA improvement: 5.8°) and trapezius muscle activation in computer users. Dunleavy et al. (2021) found that wearable biofeedback combined with exercise produced superior outcomes compared to exercise alone for FHP correction.

Multimodal Ergonomic Intervention

Ergonomics, defined as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system and the profession that applies theory, principles, data, and methods to design in order to optimize human wellbeing and overall system performance (IEA, 2000), addresses SRPD from the environmental, behavioral, and physiological levels simultaneously. A multimodal ergonomic approach integrates: (1) device and workstation configuration optimization; (2) postural and movement habit modification using behavior change theory; (3) targeted therapeutic exercise addressing strength and flexibility deficits perpetuating postural distortion; and (4) ergonomic awareness education.

Demonstrating the superiority of multimodal ergonomic approaches, Iqbal et al. (2021) reported that a 12-week multimodal ergonomic program produced significantly greater improvements in CVA (8.2° *vs* 4.1°), pain, and disability compared to exercise alone in office workers with FHP. The addition of behavioral intervention components has been shown to significantly improve long-term adherence and prevent relapse of postural dysfunction [9].

Research Gap and Justification

No previous RCT has directly compared MEI, WPBT, and SPE as distinct three-arm parallel interventions specifically targeting smartphone-induced postural dysfunction in Indian or South Asian populations. Furthermore, the behavioral dimension of smartphone-related postural dysfunction — particularly smartphone addiction and habitual use patterns — has rarely been incorporated as an outcome measure in postural rehabilitation RCTs, despite its mechanistic centrality. The present study addresses these critical gaps.

Materials and Methods

Study Design

A three-arm, parallel-group, assessor-blinded Randomized Controlled Trial was conducted at the Outpatient Physiotherapy and Occupational Health Department. The trial duration was 18 months (February 2024 – August 2025). Ethical clearance was granted by the Institutional Ethics Committee (IEC/2024/PHY/007). The trial was prospectively registered with CTRI prior to commencement of recruitment. All participants provided written informed consent prior to enrollment.

Participants

Inclusion Criteria

- Adults aged 18-40 years.
- Habitual smartphone use ≥5 hours/day for a minimum of 12 consecutive months.
- Craniovertebral Angle (CVA) ≤50° measured via standardized digital photogrammetry.
- Thoracic kyphosis angle ≥40° (flexicurve ruler measurement).
- Neck pain VAS ≥2/10.
- Neck Disability Index (NDI) score ≥10% (mild disability or above).
- Willingness to comply with intervention protocols and attend all follow-up assessments.

Exclusion Criteria

- Diagnosed structural spinal deformity (scoliosis, Scheuermann's disease, congenital kyphosis).
- History of cervical or thoracic spine surgery.
- Acute inflammatory arthropathy, ankylosing spondylitis, or rheumatoid arthritis.
- Neurological disorders affecting posture control (cerebral palsy, Parkinson's disease, cerebellar ataxia).
- Dermatological conditions precluding wearable sensor application (for Group B allocation).
- Cognitive impairment affecting informed consent or protocol comprehension.
- Concurrent physiotherapy, chiropractic, or postural intervention within 8 weeks of enrollment.
- Pregnancy or postpartum period within 6 months.

Sample Size

Sample size was estimated using G*Power 3.1 for a one-way ANOVA (three groups) with anticipated effect size f = 0.38 (medium-large, based on Iqbal et al., 2021), alpha = 0.05, power = 0.85. Minimum required sample: 34 per group. With an anticipated 15% attrition rate and the addition of a safety buffer, 40 participants per group (total N = 120) were enrolled.

Randomization and Allocation Concealment

Randomization was performed using a computer-generated random number sequence (Random Allocation Software v2.0) with a 1:1:1 allocation ratio, stratified by age (18–29 *vs* 30–40 years) and sex, using permuted blocks of size six. Allocation was concealed using sequentially numbered, opaque, sealed envelopes (SNOSE method). Envelopes were opened only after baseline assessment was completed for each participant. Outcome assessment was performed by an independent physiotherapist blinded to group allocation (assessor blinding). Blinding of participants and treating therapists was not feasible given the nature of interventions; participant blinding was addressed through careful management of patient expectations at enrollment.

Intervention Protocols

Group A: Multimodal Ergonomic Intervention (MEI) — 8 Weeks

Component 1 — Device and Environmental Ergonomic Restructuring (Week 1): An individualized ergonomic assessment of each participant's primary smartphone-use environment (home, workplace, study space) was conducted using the Rapid Upper Limb Assessment (RULA) tool adapted for smartphone use. Prescribed modifications included: optimal device height (eye level ± 15°), use of ergonomic phone stands and holders, prescribed break schedules (20-20-20 rule: every 20 minutes, 20-second break, gaze redirected ≥20 feet), screen font size optimization, and notification management to reduce compulsive checking behavior. Written ergonomic prescription was provided to each participant.

Component 2 — Targeted Therapeutic Exercise Protocol (Weeks 1–8, daily): Chin tucks (10 repetitions × 3 sets); cervical retraction in supine (10 × 3); deep cervical flexor activation via pressure biofeedback (22–28 mmHg, 10 × 10 seconds); thoracic

Table 1: Outcome Measures, Tools, Classification, and Assessment Time-Points.

Outcome Measure	Measurement Tool	Classification	Assessment Time-Points
Craniovertebral Angle (CVA)	Digital Photogrammetry	Primary	Baseline, Week 4, Week 8
Thoracic Kyphosis Index (TKI)	Flexicurve Ruler	Primary	Baseline, Week 4, Week 8
Rounded Shoulder Angle (RSA)	Digital Photogrammetry	Secondary	Baseline, Week 8
Pain Intensity (VAS)	Visual Analogue Scale	Secondary	Baseline, Week 4, Week 8
Neck Disability Index (NDI)	Validated Questionnaire	Secondary	Baseline, Week 8
Cervical Range of Motion	CROM Device	Secondary	Baseline, Week 8
Smartphone Addiction (SAS-SV)	6-item Likert Scale	Secondary	Baseline, Week 8
Daily Smartphone Use (hrs)	Self-report + Screen Time App	Secondary	Baseline, Week 4, Week 8
Treatment Adherence	Attendance Log + Device Data	Process	Weekly
Participant Satisfaction	5-point Likert Scale	Process	Week 8

extension over foam roller (2 minutes); corner chest stretch (3 × 30 seconds); scapular retraction/depression strengthening with Theraband (15 × 3); shoulder external rotation exercises (15 × 3); thoracic self-mobilization using lacrosse ball (5 minutes).

Component 3 — Behavioral Modification Program (Weeks 1–8): Based on the Transtheoretical Model and Implementation Intentions Theory, participants completed weekly behavioral goal-setting sessions. Digital habit journals (Google Forms) were maintained for daily smartphone use logging. Screen-time management apps (Digital Wellbeing/Screen Time) were configured with daily usage limits. Motivational interviewing-based counseling (3 sessions, Weeks 1, 4, 7) addressed ambivalence and reinforced behavior change. WhatsApp group for peer support and therapist check-ins.

Group B: Wearable Posture Biofeedback Training (WPBT) — 8 Weeks

Device: Lumo Lift/Upright GO 2 wearable posture trainer (IMU-based, adhesive thoracic sensor). Calibrated to participant's optimal upright posture during initial session.

Training Protocol (Weeks 1–8): Participants wore the device during all waking hours of smartphone use. The device delivered a gentle vibrotactile alert upon detection of thoracic flexion exceeding the individualized threshold (calibrated at 5° beyond optimal posture). Participants were instructed to correct posture immediately upon alert. Weekly therapist review of device data (posture score, alert frequency, wear time) was conducted for progressive threshold adjustment.

Supplementary Exercise (Weeks 1–8, 3 × per week): Chin tucks (10 × 3); scapular retraction (15 × 3); thoracic extension over foam roller (2 minutes). A standardized exercise booklet was provided.

Behavioral Component: Participants received device-generated weekly posture reports via companion app and were encouraged to set personal weekly improvement targets.

Group C: Standard Postural Education (SPE) — 8 Weeks (Active Control)

Educational Sessions: Six structured group educational sessions (Weeks 1, 2, 3, 4, 6, 8), each 45 minutes, covering: anatomy of the cervical and thoracic spine, biomechanics of smartphone-induced postural stress, principles of optimal sitting/standing posture, ergonomic principles for device use, and self-management strategies. Professionally produced illustrated handouts and a postural awareness booklet were provided.

Home Exercise Advice: Identical home exercise booklet to Group B provided at Week 1 (chin tucks, scapular retraction, foam roller extension), with no supervised sessions or progressive monitoring.

Outcome Measures

See Table 1.

Statistical Analysis

Statistical analysis was performed using IBM SPSS v26.0 and R v4.3.0. Between-group differences at baseline were examined using one-way ANOVA (continuous) or chi-square tests (categorical). The primary analysis used a mixed-model repeated measures ANOVA (MMRMA) with group as between-subject factor and time (baseline, Week 4, Week 8) as within-subject factor. Post-hoc pairwise comparisons with Bonferroni correction were applied where omnibus F-tests were significant. Effect sizes were calculated as partial eta-squared (ηp^2). Missing data were handled using multiple imputation (10 imputations). All analyses followed the intention-to-treat (ITT) principle. Per-protocol analysis was conducted as a sensitivity analysis. A priori significance threshold was $p<0.05$ (two-tailed).

Results

Participant Flow (CONSORT)

A total of 184 individuals were screened; 120 met eligibility criteria and were randomized (Group A: n=40, Group B: n=40, Group C: n=40). At Week 8, 118 participants completed the study (Group A: n=39, Group B: n=40, Group C: n=39). Two participants withdrew: one from Group A (relocation) and one from Group C (personal reasons). No adverse events related to interventions were recorded. Intention-to-treat analysis was applied to all 120 randomized participants.

Baseline Characteristics

See Table 2.

Primary Outcomes: Craniovertebral Angle (CVA)

Between-group differences in CVA change from baseline to Week 8 were statistically significant ($F(2,117) = 38.4$, $p<0.001$, $\eta p^2 = 0.396$, large effect). Post-hoc pairwise comparisons with Bonferroni correction confirmed significant differences between all three groups (A *vs* B: p=0.028; A vs C: p<0.001; B vs C: p<0.001) (Table 3).

Table 2: Baseline Demographic and Clinical Characteristics (Mean ± SD; all p>0.05 confirming comparability).

Variable	Group A: MEI (n=40)	Group B: WPBT (n=40)	Group C: SPE (n=40)	p-value
Mean Age (years)	26.8 ± 5.4	27.3 ± 5.8	26.4 ± 5.1	0.802
Sex (M: F)	19:21	20:20	18:22	0.894
Smartphone Use (hrs/day)	6.9 ± 1.5	7.2 ± 1.4	6.7 ± 1.6	0.352
Baseline CVA (degrees)	44.2 ± 4.1	43.9 ± 3.8	44.6 ± 4.3	0.724
Baseline TKI	42.8 ± 5.2	43.4 ± 4.9	42.2 ± 5.6	0.614
Baseline VAS (0–10)	5.2 ± 1.4	5.4 ± 1.3	5.1 ± 1.5	0.672
Baseline NDI (%)	26.4 ± 8.1	27.2 ± 7.6	25.8 ± 8.4	0.742
Baseline SAS-SV	22.4 ± 5.8	23.1 ± 6.2	22.8 ± 5.4	0.864

Table 3: CVA Changes Across Groups (*** p<0.001 vs baseline; Higher CVA = Better Posture).

Group	Baseline CVA (°)	Week 4 CVA (°)	Week 8 CVA (°)	Net Change (°)
A: MEI	44.2 ± 4.1	49.1 ± 3.8	53.6 ± 3.2	+9.4 ± 2.1 ***
B: WPBT	43.9 ± 3.8	47.8 ± 3.6	51.2 ± 3.4	+7.3 ± 2.4 ***
C: SPE	44.6 ± 4.3	46.2 ± 4.1	48.4 ± 4.0	+3.8 ± 1.9 ***

Table 4: Secondary Outcome Comparison at Week 8 Across Groups (All between-group differences p<0.05).

Outcome	Group A: MEI	Group B: WPBT	Group C: SPE	Best
VAS Reduction (%)	48.1%	52.8%	28.4%	B
NDI Improvement (%)	51.4%	46.2%	24.8%	A
RSA Improvement (°)	8.6 ± 2.1	7.2 ± 1.9	3.4 ± 1.6	A
SAS-SV Reduction (%)	34.2%	18.6%	12.4%	A
Daily Use Reduction (hrs)	2.4 ± 0.8	1.2 ± 0.6	0.6 ± 0.5	A
Adherence Rate (%)	76.4%	82.4%	64.2%	B
Participant Satisfaction	4.6/5	4.4/5	3.8/5	A

Primary Outcome: Thoracic Kyphosis Index (TKI)

All three groups showed significant TKI reduction (improvement). Group A demonstrated the largest reduction (TKI: 42.8 → 34.6, mean reduction 8.2°, p<0.001), followed by Group B (43.4 → 37.1, mean reduction 6.3°, p<0.001) and Group C (42.2 → 39.4, mean reduction 2.8°, p<0.001). Between-group differences were statistically significant ($F(2,117) = 29.6$, $p<0.001$, $\eta p^2 = 0.336$).

Secondary Outcomes Summary

See Table 4.

Predictor Analysis

Multivariate linear regression analysis identified baseline CVA (β = -0.42, p<0.001), daily smartphone use duration (β = -0.31, p=0.004), and baseline SAS-SV score (β = -0.27, p=0.018) as significant independent predictors of CVA improvement at Week 8, irrespective of intervention group. Younger age (18–25 years) was associated with greater improvement in behavioral outcomes (SAS-SV, daily use) but not in postural parameters. These findings support individualized intervention selection based on baseline behavioral and postural profiles.

Discussion

Superior Efficacy of MEI for Postural Correction

The Multimodal Ergonomic Intervention produced the greatest improvements in both primary postural outcomes (CVA and TKI) and in secondary behavioral outcomes (SAS-SV, daily use duration). These results are consistent with the established hierarchy of ergonomic control, which prioritizes environmental modification over personal protective equipment and administrative controls. By restructuring the physical environment of smartphone use, MEI addresses the root cause of postural dysfunction at the source, rather than relying solely on the individual's willingness and ability to self-correct in the absence of environmental supports.

The CVA improvement of 9.4° in Group A substantially exceeds the previously reported Minimal Detectable Change (MDC) for CVA of 5.0° [14] and the Minimum Clinically Important Difference (MCID) estimated at 5–6° in the literature, confirming that the improvements observed were not only statistically significant but clinically meaningful. The behavioral modification component of MEI, grounded in Implementation Intentions Theory, was likely responsible for the superior behavioral outcomes in Group A, as forming specific 'if-then' implementation intentions ('If I pick up my phone, then I will raise it to eye level before using it') has been shown to substantially increase the likelihood of behavior change maintenance [4].

Value of Wearable Biofeedback

Group B's superior short-term adherence rate (82.4%) and pain reduction outcomes (VAS: 52.8% reduction) underscore the unique contribution of real-time biofeedback to compliance and immediate postural correction. The operant conditioning mechanism — whereby the vibrotactile alert serves as an immediate aversive consequence of postural lapse — is neurophysiologically potent and temporally immediate in a way that delayed or voluntary correction strategies cannot replicate. This is particularly significant in clinical contexts where pain is the primary presenting complaint, as WPBT may facilitate faster pain relief through consistent postural offloading of sensitized cervical structures.

However, the lower behavioral and long-term structural outcomes of WPBT compared to MEI suggest that biofeedback device use does not inherently produce the environmental modifications or deep behavioral change required for sustained postural improvement independent of device use. This is consistent with findings from [3], who noted postural relapse following cessation of biofeedback device use in the absence of comprehensive behavioral programming.

Limitations of Standard Postural Education

Group C's statistically significant but clinically modest improvements across all outcome domains affirm that postural education produces genuine but limited benefit when delivered without environmental or real-time behavioral support. This finding corroborates the extensive behavior change literature indicating that knowledge-intention-behavior gaps are common and large in health-related behaviors [10]. Physiotherapy practice should recognize SPE as a necessary but insufficient intervention for SRPD, appropriately used as a component of, rather than a substitute for, comprehensive ergonomic intervention.

Integrated MEI-WPBT Protocol Recommendation

The complementary efficacy profiles of MEI and WPBT — MEI providing superior environmental restructuring, behavioral modification, and long-term structural improvement; WPBT providing superior real-time compliance support and acute pain relief — provide a compelling rationale for an integrated protocol. The recommended clinical pathway is: Weeks 1–2: Initiate MEI (ergonomic assessment and restructuring, exercise initiation, behavioral goal-setting) concurrent with WPBT (device calibration, threshold-setting); Weeks 3–6: Full MEI protocol with WPBT worn during all smartphone use; Weeks 7–8: Gradual WPBT weaning with consolidated MEI behavioral and environmental modifications; Post-treatment: MEI home program and periodic ergonomic reassessment at 3 and 6 months.

Implications for BPT Education

The findings of this study have direct implications for undergraduate physiotherapy education. The BPT curriculum should incorporate dedicated modules in ergonomics and occupational health, behavioral change counseling techniques, wearable technology assessment and prescription, and postural rehabilitation across diverse digital device use contexts. Clinical educators should equip future physiotherapists with the competency to conduct individualized ergonomic assessments and to design multimodal, behaviorally-informed postural correction programs.

Limitations

- Single-center design limits generalizability; multi-center replication is warranted.
- Wearable device brand heterogeneity was minimized but not eliminated across the WPBT group.
- Long-term follow-up beyond 8 weeks was not conducted; future studies should include 6- and 12-month assessments.
- Self-reported smartphone use data are subject to recall bias, partially mitigated by screen-time app verification.
- Socioeconomic factors affecting device type, posture at work, and ergonomic modification feasibility were not fully controlled.

Conclusion

This three-arm randomized controlled trial provides robust evidence that Multimodal Ergonomic Intervention (MEI) produces the greatest and most comprehensive improvements in craniovertebral angle, thoracic kyphosis, disability, and behavioral smartphone habits among adults with smartphone-related postural dysfunction. Wearable Posture Biofeedback Training (WPBT) provides complementary superiority in short-term adherence and pain relief through real-time operant conditioning mechanisms. Standard Postural Education, while producing significant improvements, is insufficient as a standalone intervention for clinically meaningful and durable postural correction.

An integrated MEI-WPBT protocol is recommended as the evidence-based standard of care for SRPD management in physiotherapy clinical practice. Future research should examine the cost-effectiveness of MEI-WPBT integration, explore the role of artificial intelligence-enhanced biofeedback systems, and evaluate long-term outcomes at 6 and 12 months post-intervention. Physiotherapy educational programs are strongly encouraged to integrate multimodal ergonomic assessment and wearable technology prescription competencies into the BPT curriculum.

Declarations

Conflict of Interest: None declared.

Funding: Wearable devices for Group B were partially provided on loan by a clinical supplier for the duration of the trial at no cost to participants; devices were returned post-trial. No financial sponsorship was received.

Ethical Approval: Institutional Ethics Committee, IEC/2024/PHY/007. All participants provided written informed consent.

Data Availability: Anonymized participant-level data are available from the corresponding author on reasonable request following institutional data-sharing agreement.

Author Contributions: MS: conceptualization, study design, data acquisition, analysis, manuscript drafting. PR: intervention delivery, data collection, manuscript review. Both authors approved the final manuscript.

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