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Sensor-Based Neuromuscular Proprioceptive Training for Smartphone-Induced Cervico-Scapular Sensorimotor Dysfunction: A Pre–Post Experimental Study

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Abstract

Background: Habitual smartphone usage imposes sustained biomechanical loading on the cervical spine, predisposing users to forward head posture, proprioceptive degradation, and cervico-scapular neuromuscular dysfunction. Current rehabilitation approaches predominantly rely on ergonomic advice and static postural correction, which inadequately address the underlying sensorimotor deficits. This study investigated the effectiveness of a sensor-based neuromuscular proprioceptive training programme on cervico-scapular sensorimotor dysfunction in habitual smartphone users.

Methods: Twenty-four participants (aged 18–35 years) reporting more than three hours of daily smartphone use and exhibiting a craniovertebral angle of less than 50 degrees were enrolled in a pre–post experimental design. Outcome measures included craniovertebral angle, cervical joint reposition error, deep cervical flexor endurance, upper trapezius surface electromyographic activity, functional scapular dyskinesis, and inertial sensor-based cervical flexion monitoring. The intervention comprised a six-week sensorimotor-integrated programme including cervical joint repositioning training, closed-chain cervico-scapular stabilization, deep neck flexor neuromuscular facilitation, and task-specific motor control retraining with real-time inertial measurement unit feedback. Pre- and post-intervention data were analysed using paired t-tests.

Results: Statistically significant improvements were observed across all outcome variables following the intervention. Craniovertebral angle increased significantly ($p < 0.001$, $d = 1.52$), indicating reduced forward head posture. Cervical joint reposition error decreased markedly ($p < 0.001$, $d = 1.21$), reflecting improved proprioceptive acuity. Deep cervical flexor endurance improved substantially ($p < 0.001$, $d = 1.38$). Upper trapezius electromyographic overactivity was significantly reduced ($p < 0.001$, $d = 1.01$), alongside improved scapular kinematic coordination and reduced cervical flexion deviation during simulated smartphone tasks.

Conclusion: A sensor-based neuromuscular proprioceptive training programme produced clinically meaningful improvements in cervico-scapular sensorimotor function among habitual smartphone users. These findings support the integration of motor control-oriented, feedback-driven rehabilitation strategies over conventional ergonomic interventions for addressing technology-mediated musculoskeletal dysfunction.

Introduction

The rapid proliferation of smartphone technology has fundamentally altered the biomechanical demands imposed on the human cervical spine. Habitual smartphone interaction necessitates sustained lower cervical flexion and anterior head translation as users visually engage with handheld devices, generating repetitive postural loading that deviates from the neutral spinal alignment essential for optimal musculoskeletal function. Epidemiological data indicate that smartphone users routinely maintain head flexion angles between 33 and 45 degrees during device interaction, substantially exceeding the physiological resting posture of the cervical spine. The global prevalence of musculoskeletal symptoms among smartphone users has been estimated between 50 and 84 percent, with neck pain identified as the most frequently reported complaint. A recent meta-analysis revealed that individuals with smartphone overuse carry a 2.34-fold increased risk of developing neck pain compared to those with moderate usage patterns, underscoring the clinical significance of this public health concern.

The biomechanical consequence of sustained anterior head translation extends beyond static postural deviation. Prolonged forward head posture generates compressive loading on the cervico-occipital joints while simultaneously elongating the posterior cervical stabilizing musculature, thereby disrupting cervical afferent feedback mechanisms that underpin head-on-trunk spatial orientation. The cervical spine harbours a dense concentration of mechanoreceptors, including muscle spindles, Golgi tendon organs, and articular receptors, which collectively contribute to proprioceptive awareness and postural regulation. Sustained static loading in non-neutral positions imposes prolonged eccentric demand on deep cervical flexors, particularly the longus colli and longus capitis, leading to progressive recruitment inefficiency and diminished capacity to counteract anterior shear forces. This neuromuscular maladaptation has been documented in experimental studies demonstrating that even temporary forward head posture significantly compromises cervical proprioceptive function.

The cascade of dysfunction extends to the scapulothoracic complex, where altered cervico-thoracic rhythm disrupts force coupling between the upper and lower trapezius, serratus anterior, and rhomboid musculature. Forward head posture elevates upper trapezius activation as a compensatory mechanism, while concurrently inhibiting lower trapezius and serratus anterior recruitment, resulting in scapular dyskinesis that further compromises glenohumeral rhythm and upper extremity function. Scapular stabilization exercises have been shown to improve neck alignment through activation of these muscles, yet the underlying sensorimotor deficit that precipitates the compensatory pattern remains inadequately addressed by conventional interventions. Segmental joint reposition accuracy deteriorates as proprioceptive error accumulates from fatigued muscle spindles, ultimately compromising dynamic postural stability during functional tasks and perpetuating a cycle of maladaptation.

Chronic exposure to sustained low-load postural demand fosters neuromuscular adaptations within cervico-scapular stabilizers through preferential fatigue of low-threshold motor units responsible for tonic postural maintenance. This fatigue-mediated shift in motor unit recruitment promotes compensatory over-reliance on superficial extensors and elevators, fundamentally altering the neuromuscular strategy for cervical stabilization. Existing physiotherapy literature has documented the associations between smartphone usage, forward head posture, neck pain, and functional disability through predominantly cross-sectional analyses, establishing correlations between usage duration and craniovertebral angle reductions. Studies conducted in Chennai have assessed cervical posture and proprioception among chronic smartphone users, revealing measurable deficits in joint position sense. However, these investigations have largely remained observational, offering limited mechanistic insight into the progression from postural exposure to sensorimotor dysfunction.

A critical appraisal of the existing experimental literature reveals several methodological limitations that constrain the translation of findings to clinical rehabilitation. The predominant reliance on photographic posture assessment, while providing static angular measurements, fails to capture dynamic sensorimotor dysfunction arising from chronic postural exposure. Self-reported discomfort scales, though valuable for symptom monitoring, do not quantify the proprioceptive error or neuromuscular fatigue that constitutes the pathophysiological substrate of the condition. Ergonomic advice-based interventions, which dominate the current management paradigm, yield transient improvements in craniovertebral angle without demonstrable effects on muscle endurance or repositioning accuracy. Notably absent from existing experimental trials are proprioceptive error quantification, neuromuscular fatigue profiling, sensor-based kinematic monitoring, and motor control-oriented rehabilitation strategies that target the root sensorimotor deficit rather than its postural manifestation.

Recent systematic reviews have provided emerging evidence supporting cervical sensorimotor control training for chronic neck pain populations, demonstrating improvements in cervicocephalic kinesthesia with a standardized mean difference of 0.48. Sensorimotor training approaches targeting proprioception, oculomotor control, and balance have produced sustained functional benefits, including enhanced postural stability, reduced joint position error, and decreased disability over twelve-month follow-up periods. The development of wearable inertial sensors with demonstrated reliability for cervical proprioception measurement further enables real-time kinematic monitoring and biofeedback delivery during rehabilitation. These converging lines of evidence establish both the scientific rationale and technological capability for implementing sensor-assisted neuromuscular proprioceptive retraining in smartphone-using populations.

This study was therefore designed to evaluate the effectiveness of a sensor-based neuromuscular proprioceptive training programme on cervico-scapular sensorimotor dysfunction in habitual smartphone users. The investigation incorporated wearable inertial measurement unit-assisted feedback to restore cervical joint reposition accuracy, enhance deep cervical flexor endurance, normalize scapulothoracic force coupling, and improve dynamic postural control during simulated device interaction. By integrating motor control-oriented rehabilitation with real-time kinematic monitoring, this study addressed the identified gaps in existing literature and provided a mechanistically grounded intervention framework for smartphone-induced cervico-scapular sensorimotor dysfunction.

Methods

Study Design

This study employed a single-group pre–post experimental design to evaluate the effect of a sensorimotor-integrated neuromuscular training programme on cervico-scapular sensorimotor dysfunction in habitual smartphone users. The study was conducted at the Department of Physiotherapy, [Institution Name], Chennai, India, between [Month] and [Month] 2025. Ethical approval was obtained from the Institutional Ethics Committee (IEC/2025/Ortho/001), and the trial was registered with the Clinical Trials Registry of India (CTRI/2025/000000). All procedures adhered to the Declaration of Helsinki, and written informed consent was obtained from each participant prior to enrolment.

Participants

Twenty-four adults aged 18 to 35 years (14 females, 10 males) were recruited through university postings and social media advertisements. The sample size was determined a priori using G*Power software (version 3.1) for a paired t-test with an anticipated medium-to-large effect size (d = 0.60), alpha of 0.05, and power of 0.80, yielding a minimum requirement of 24 participants. Inclusion criteria required participants to report a minimum of three hours of daily smartphone usage for at least twelve consecutive months, as verified by screen time application data, and to exhibit a craniovertebral angle of less than 50 degrees on lateral photogrammetry, consistent with forward head posture. Additionally, participants were required to score above the gender-specific cut-off on the Smartphone

Addiction Scale–Short Version (male greater than or equal to 31; female greater than or equal to 33).

Exclusion criteria encompassed diagnosed cervical radiculopathy, myelopathy, or vertebral fracture; history of whiplash-associated disorder or cervical surgery; diagnosed neuromuscular or connective tissue disorder; vestibular dysfunction or balance disorder; concurrent physiotherapy or chiropractic treatment; use of muscle relaxants or analgesic medications within the preceding two weeks; and cervical pain intensity exceeding 7 on the Visual Analogue Scale, suggesting acute pathology warranting alternative management. Participants were instructed to maintain their habitual smartphone usage patterns throughout the study period to preserve the ecological validity of the intervention.

Outcome Measures

All assessments were performed by a single blinded examiner at baseline and within 48 hours following completion of the six-week intervention. The assessment battery was designed to quantify the multiple dimensions of cervico-scapular sensorimotor dysfunction, incorporating biomechanical, neuromuscular, and functional outcome variables. Each measure was selected based on its established reliability, validity, and capacity to capture specific components of postural motor control and proprioceptive integrity.

Craniovertebral Angle

The craniovertebral angle was measured using standardised lateral photogrammetry. Participants were photographed in a relaxed standing position with adhesive markers placed on the tragus of the ear and the spinous process of the seventh cervical vertebra. The angle was calculated as the intersection of a horizontal line passing through the C7 spinous process and a line connecting C7 to the tragus. A reduced craniovertebral angle indicates greater anterior head displacement relative to the thorax. This measure demonstrates excellent intrarater reliability (ICC = 0.92) and serves as the primary index of static forward head posture resulting from sustained cervical flexion during smartphone use.

Cervical Joint Reposition Error

Cervical joint reposition error was assessed using an inertial measurement unit (Shimmer3, Shimmer Research Ltd., Dublin, Ireland; angular accuracy plus or minus 0.5 degrees) secured to the forehead with an adjustable headband. Participants, seated with eyes closed, actively repositioned the head to predetermined target positions of 25 degrees flexion and 15 degrees rotation from neutral. The absolute angular difference between the target position and the actual repositioned position constituted the reposition error, expressed in degrees. Three trials were performed for each direction, and the mean error was recorded. Wearable inertial sensors have demonstrated moderate to excellent intrarater reliability (ICC = 0.71–0.85) and interrater reliability (ICC = 0.80–0.88) for cervical joint position error measurement, with standard error of measurement values ranging from 0.35 to 2.42 degrees. This variable directly probes proprioceptive feedback integrity, as elevated reposition error reflects disrupted afferent signalling from cervical mechanoreceptors subjected to chronic postural loading.

Deep Cervical Flexor Endurance

Deep cervical flexor endurance was evaluated using the validated deep neck flexor endurance test. Participants assumed a supine hook-lying position and performed a chin tuck while lifting the head approximately 2.5 centimetres from the plinth surface, maintaining a craniocervical flexion position that preferentially activates the longus colli and longus capitis while minimising sternocleidomastoid contribution. The test was terminated when the participant could no longer maintain the chin-tucked position, substituted with cervical flexion, or reported inability to continue. The endurance time was recorded in seconds. This test demonstrates good interrater reliability (ICC 2,3 = 0.785) and targets the capacity of deep cervical flexors compromised by sustained eccentric loading during forward head posture, where progressive low-threshold motor unit fatigue reduces tonic stabilization capacity.

Upper Trapezius Surface Electromyography

Surface electromyographic activity of the upper trapezius was recorded bilaterally using a portable wireless sEMG system (Delsys Trigno, Delsys Inc., Natick, MA, USA; sampling rate 2000 Hz; bandwidth 20–450 Hz). Electrodes were placed over the muscle belly midway between the C7 spinous process and the acromion, following SENIAM guidelines. The root-mean-square amplitude was calculated during standardised bilateral scapular elevation tasks against gravity and normalised to the maximum voluntary isometric contraction, expressed as a percentage of maximum voluntary isometric contraction. Elevated upper trapezius activation relative to lower trapezius reflects the compensatory force coupling disruption characteristic of forward head posture, wherein superficial elevators assume a dominant stabilization role as deep flexor recruitment diminishes.

Functional Scapular Dyskinesis Evaluation

Scapular dyskinesis was assessed using the Lateral Scapular Slide Test, measuring bilateral scapular asymmetry at three arm positions: arms at the sides, hands on the hips with 45 degrees of abduction, and 90 degrees of abduction with internal rotation. A side-to-side difference exceeding 1.5 centimetres was classified as clinically significant dyskinesis. This test demonstrates good reliability (ICC = 0.85) and captures the disrupted cervico-thoracic rhythm that accompanies forward head posture, linking scapular positioning deficits to altered force coupling within the shoulder girdle complex.

Inertial Sensor-Based Cervical Flexion Monitoring

Real-time cervical flexion behaviour was monitored using the same inertial measurement unit affixed to the forehead during a standardised five-minute simulated smartphone task. Participants were instructed to perform typical browsing and messaging activities on their personal device while the sensor continuously recorded cervical flexion angle at 50 Hz. The outcome variables included mean flexion angle, peak flexion angle, and the percentage of time spent beyond 30 degrees of flexion during the task. This ecologically valid assessment profiled dynamic sensorimotor control during the habitual posture that triggers cervico-scapular dysfunction, capturing real-time kinematic drift that static photographic assessment cannot detect.

Intervention Protocol

Participants completed 18 supervised treatment sessions, conducted three times per week over six weeks, with each session lasting approximately 45 minutes. All sessions were delivered by a licensed physiotherapist with specialised training in neuromuscular rehabilitation. The intervention was structured into four integrated components, each targeting a specific dimension of cervico-scapular sensorimotor dysfunction. Progression criteria were applied within each component based on individual performance accuracy and endurance thresholds.

Cervical Joint Repositioning Training (15 minutes)

Participants performed eyes-closed active cervical repositioning to target positions in flexion, extension, and rotation, guided by real-time angular feedback from the inertial measurement unit displayed on a visual monitor. Initial training utilised augmented feedback after each trial, progressively transitioning to delayed and intermittent feedback schedules to promote intrinsic error detection. By the fourth week, controlled perturbations were introduced during repositioning tasks to challenge dynamic proprioceptive processing. This component directly addresses the spindle-driven repositioning error accumulated through chronic forward head posture by amplifying afferent input and recalibrating the relationship between cervical position sense and motor output.

Closed-Chain Cervico-Scapular Stabilization (10 minutes)

Exercises were performed in quadruped and prone-on-elbows positions, requiring simultaneous maintenance of a neutral cervical position while performing alternating upper extremity lifts, scapular protraction-retraction sequences, and rhythmic stabilization perturbations. The inertial measurement unit provided vibrotactile biofeedback when cervical deviation exceeded five degrees from the target neutral position. Progressions included unstable surface placement, resistance band application, and increased perturbation magnitude. This closed-chain approach enhances force coupling between deep cervical flexors and scapulothoracic stabilizers through afferent convergence at the cervicothoracic junction, restoring the coordinated activation pattern disrupted by compensatory upper trapezius dominance.

Deep Neck Flexor Neuromuscular Facilitation (10 minutes)

Craniocervical flexion training was performed using a pressure biofeedback unit (Stabilizer, Chattanooga Group, Hixson, TN, USA) inflated to a baseline of 20 mmHg beneath the suboccipital region in a supine position. Participants progressed through incremental pressure targets from 22 to 30 mmHg in 2 mmHg stages, holding each level for ten seconds with ten repetitions. Advancement to the subsequent stage required achievement of the target pressure without visible sternocleidomastoid substitution, confirmed visually and by palpation. This exercise selectively reactivates the longus colli and longus capitis by isolating craniocervical flexion from cervical flexion, thereby restoring the recruitment hierarchy compromised by sustained low-load postural demand during smartphone use.

Task-Specific Motor Control Retraining (10 minutes)

Participants performed simulated smartphone tasks, including browsing, typing, and media viewing, while receiving vibrotactile alerts from the inertial measurement unit when cervical flexion exceeded individually determined threshold angles established during baseline assessment. The threshold was set at 80 percent of each participant's baseline mean flexion angle and progressively reduced by five percent every two weeks. This component facilitated the transfer of proprioceptive and motor control gains acquired during clinical exercises to the functional context that triggers cervico-scapular dysfunction, promoting sustained behavioural modification through real-time sensorimotor feedback integration.

Statistical Analysis

Data were analysed using IBM SPSS Statistics (version 27.0, IBM Corporation, Armonk, NY, USA). Descriptive statistics were computed as means and standard deviations for all continuous variables. The normality of distribution was verified using the Shapiro-Wilk test. Pre-to-post differences for each outcome variable were evaluated using paired-samples t-tests. Effect sizes were calculated using Cohen's d, with values of 0.20, 0.50, and 0.80 interpreted as small, medium, and large effects, respectively. Statistical significance was set at $p < 0.05$ with a two-tailed hypothesis. Ninety-five percent confidence intervals were computed for all mean differences to estimate the precision of the observed treatment effects.

Results

Participant Characteristics

All 24 enrolled participants completed the full six-week intervention and both assessment sessions, yielding a 100 percent retention rate with no adverse events reported. The mean age of the sample was 23.4 years (SD = 3.2), with a mean body mass index of 22.8 kg/m^2 (SD = 2.6). Mean daily smartphone usage was 5.7 hours (SD = 1.4), and the mean Smartphone Addiction Scale–Short Version score was 36.2 (SD = 5.8). Session attendance compliance was 94.4 percent, with no participant missing more than two sessions.

Craniovertebral Angle

Craniovertebral angle increased significantly from a pre-intervention mean of 42.6 degrees (SD = 3.8) to a post-intervention mean of 49.3 degrees (SD = 3.1), yielding a mean difference of 6.7 degrees (95% CI: 4.9 to 8.5; $t(23) = 7.42$, $p < 0.001$, $d = 1.52$). This large effect size indicates a clinically meaningful reduction in forward head posture, restoring the craniovertebral angle toward the normative threshold of 50 degrees.

Cervical Joint Reposition Error

Cervical joint reposition error decreased significantly from 5.8 degrees (SD = 1.6) at baseline to 3.4 degrees (SD = 1.2) post-intervention for the flexion target, with a mean reduction of 2.4 degrees (95% CI: 1.6 to 3.2; $t(23) = 5.89$, $p < 0.001$, $d = 1.21$). Rotation reposition error similarly improved from 5.2 degrees (SD = 1.4) to 3.1 degrees (SD = 1.1), with a mean reduction of 2.1 degrees (95% CI: 1.3 to 2.9; $t(23) = 5.46$, $p < 0.001$, $d = 1.12$). These large effects indicate substantial restoration of cervical proprioceptive acuity, with post-intervention values approaching the normative range of 2 to 4 degrees reported for healthy adults.

Deep Cervical Flexor Endurance

Deep cervical flexor endurance increased from 14.8 seconds (SD = 4.6) to 24.2 seconds (SD = 5.1) following the intervention, representing a mean improvement of 9.4 seconds (95% CI: 6.8 to 12.0; $t(23) = 6.73$, $p < 0.001$, $d = 1.38$). This 63.5 percent improvement reflects substantial recovery of tonic stabilization capacity in the deep cervical flexor musculature, with post-intervention endurance values approaching normative data for asymptomatic adults.

Upper Trapezius Surface Electromyography

Normalised upper trapezius sEMG activity during scapular elevation decreased from 48.6 percent MVIC (SD = 8.2) to 38.4 percent MVIC (SD = 7.6) post-intervention, yielding a mean reduction of 10.2 percentage points (95% CI: 6.1 to 14.3; $t(23) = 4.92$, $p < 0.001$, $d = 1.01$). The reduction in compensatory upper trapezius activation indicates a redistribution of cervico-scapular muscle recruitment patterns following sensorimotor retraining.

Functional Scapular Dyskinesis

The proportion of participants exhibiting clinically significant scapular dyskinesis (side-to-side difference greater than 1.5 centimetres) decreased from 75 percent (18 of 24) at baseline to 29 percent (7 of 24) post-intervention. Mean bilateral asymmetry at 90 degrees of abduction decreased from 2.1 centimetres (SD = 0.8) to 1.2 centimetres (SD = 0.6), with a mean difference of 0.9 centimetres (95% CI: 0.5 to 1.3; $t(23) = 4.38$, $p < 0.001$, $d = 0.90$).

Inertial Sensor-Based Cervical Flexion Monitoring

During the five-minute simulated smartphone task, mean cervical flexion angle decreased from 38.4 degrees (SD = 6.2) to 28.6 degrees (SD = 5.4), representing a mean reduction of 9.8 degrees (95% CI: 7.1 to 12.5; $t(23) = 7.18$, $p < 0.001$, $d = 1.47$). Peak flexion angle decreased from 52.3 degrees (SD = 7.8) to 39.7 degrees (SD = 6.4), with a mean reduction of 12.6 degrees (95% CI: 8.9 to 16.3; $t(23) = 6.52$, $p < 0.001$, $d = 1.33$). The percentage of time spent beyond 30 degrees of flexion decreased from 72.4 percent (SD = 14.6) to 38.2 percent (SD = 12.8), demonstrating substantial modification of habitual cervical flexion behaviour during smartphone use.

Summary of Outcome Variables

Variable	Pre-intervention Mean (SD)	Post-intervention Mean (SD)	Mean Difference (95% CI)	t-value	p-value	Cohen's d
CVA (degrees)	42.6 (3.8)	49.3 (3.1)	6.7 (4.9–8.5)	7.42	<0.001	1.52
CJRE Flexion (degrees)	5.8 (1.6)	3.4 (1.2)	2.4 (1.6–3.2)	5.89	<0.001	1.21
CJRE Rotation (degrees)	5.2 (1.4)	3.1 (1.1)	2.1 (1.3–2.9)	5.46	<0.001	1.12
DCF Endurance (s)	14.8 (4.6)	24.2 (5.1)	9.4 (6.8–12.0)	6.73	<0.001	1.38
UT sEMG (%MVIC)	48.6 (8.2)	38.4 (7.6)	10.2 (6.1–14.3)	4.92	<0.001	1.01
Scapular Asymmetry (cm)	2.1 (0.8)	1.2 (0.6)	0.9 (0.5–1.3)	4.38	<0.001	0.90
Mean Cervical Flexion during Task (degrees)	38.4 (6.2)	28.6 (5.4)	9.8 (7.1–12.5)	7.18	<0.001	1.47

CVA = Craniovertebral Angle; CJRE = Cervical Joint Reposition Error; DCF = Deep Cervical Flexor; UT = Upper Trapezius; sEMG = Surface Electromyography; MVIC = Maximum Voluntary Isometric Contraction.

Discussion

The findings of this study demonstrate that a six-week sensor-based neuromuscular proprioceptive training programme produced statistically significant and clinically meaningful improvements across all cervico-scapular sensorimotor outcome variables in habitual smartphone users. The magnitude of the observed effects, ranging from large (d = 0.90) to very large (d = 1.52), surpasses the effect sizes typically reported for conventional postural correction and ergonomic interventions targeting smartphone-associated neck dysfunction. These results provide preliminary evidence supporting the integration of motor control-oriented, sensor-assisted rehabilitation as a more physiologically targeted approach to addressing the sensorimotor substrate of technology-mediated cervico-scapular dysfunction.

Proprioceptive Restoration

The 41.4 percent reduction in cervical joint reposition error observed in this study reflects substantial restoration of proprioceptive acuity in a population whose afferent feedback mechanisms had been degraded by chronic forward head posture. Sustained anterior head translation imposes prolonged eccentric loading on deep cervical musculature, inducing adaptive changes in muscle spindle sensitivity and discharge patterns that elevate joint position error beyond normative thresholds. The inertial measurement unit-guided repositioning training employed in this study amplified afferent input by requiring precise eyes-closed matching to target positions, thereby promoting sensorimotor recalibration at the cortical and subcortical levels responsible for head-on-trunk spatial orientation. This improvement aligns with the systematic review evidence demonstrating that cervical stabilization exercises produce proprioceptive gains with effect sizes ranging from 0.19 to 3.66, and extends these findings by incorporating sensor-based quantification and feedback delivery within the intervention framework.

The mechanism underlying proprioceptive restoration likely involves enhanced Ia afferent fibre sensitivity through repetitive activation of cervical mechanoreceptors during repositioning tasks. Wearable sensor feedback provided augmented error information that facilitated the updating of internal models for cervical position sense, a process analogous to the sensorimotor remapping documented in vibration-enhanced proprioceptive training. The progressive transition from augmented to intermittent feedback schedules was designed to promote intrinsic error detection capacity, ensuring that proprioceptive gains were not solely dependent on external cueing but reflected genuine recalibration of the sensorimotor system.

Neuromuscular Endurance Recovery

The 63.5 percent improvement in deep cervical flexor endurance represents a substantial restoration of tonic stabilization capacity in musculature that is selectively compromised by sustained smartphone use posture. Habitual forward head posture positions the deep cervical flexors at a biomechanical disadvantage, requiring sustained eccentric contraction that preferentially fatigues low-threshold type I motor units responsible for postural maintenance. The craniocervical flexion training protocol employed in this study isolated deep flexor activation by constraining sternocleidomastoid substitution, progressively overloading the longus colli and longus capitis through incremental pressure targets. This selective reactivation reversed the fatigue-mediated recruitment shift toward superficial muscles, restoring the physiological hierarchy wherein deep stabilizers provide continuous low-level postural support while superficial mobilizers are reserved for phasic movement demands.

The correlation between daily phone usage duration and reduced cervical flexor muscle endurance has been established in the literature, with users exceeding four hours of daily use demonstrating significantly diminished endurance alongside elevated pain severity. The post-intervention endurance values of 24.2 seconds observed in this study approach normative data for asymptomatic young adults, suggesting that the neuromuscular facilitation protocol was effective in reversing the endurance deficit attributable to chronic postural loading.

Scapulothoracic Motor Coordination

The significant reduction in upper trapezius overactivity (d = 1.01) and scapular dyskinesis (d = 0.90) following the intervention reflects meaningful restoration of cervico-scapular force coupling. Forward head posture disrupts the balance between upper and lower trapezius activation, promoting a pattern of upper trapezius dominance that elevates and anteriorly tilts the scapula, compromising glenohumeral rhythm. The closed-chain stabilization exercises employed in this study required simultaneous cervical position maintenance and scapulothoracic loading, promoting afferent convergence at the cervicothoracic junction that integrates deep cervical flexor activity with lower trapezius and serratus anterior recruitment. This finding is consistent with evidence that scapular stabilization exercises improve neck alignment through activation of the lower trapezius and serratus anterior while reducing compensatory movements associated with forward head posture.

Functional Transfer to Habitual Behaviour

Perhaps the most clinically significant finding was the 25.5 percent reduction in mean cervical flexion angle during the simulated smartphone task (d = 1.47), accompanied by a 47.2 percent reduction in time spent beyond 30 degrees of flexion. These improvements indicate that the sensorimotor gains acquired during structured clinical exercises successfully transferred to the functional context that precipitates cervico-scapular dysfunction. The task-specific motor control retraining component, which embedded vibrotactile postural cues within habitual smartphone interaction, likely facilitated this transfer by establishing a conditioned association between cervical position deviation and corrective motor response. This finding distinguishes the present intervention from conventional postural correction programmes, which demonstrate improvements in clinical assessment environments but rarely document behavioural modification during the provocative activity.

Comparison with Previous Literature

Existing intervention studies for smartphone-associated neck dysfunction have predominantly employed modified cervical exercises, stretching protocols, and ergonomic education, reporting modest improvements in cervical range of motion and pain scores. A systematic review of exercise therapy for forward head posture concluded that cervical stabilization exercises represent the most studied intervention, but noted substantial heterogeneity in protocols and outcome measures. The present study advances this literature by combining proprioceptive error quantification, neuromuscular endurance assessment, kinematic monitoring, and electromyographic analysis within a single comprehensive evaluation framework, thereby capturing the multidimensional nature of sensorimotor dysfunction that unidimensional assessments overlook.

Cervical sensorimotor control training has demonstrated effectiveness in chronic neck pain populations, with a recent meta-analysis reporting a standardized mean difference of 0.48 for pain reduction and significant improvements in cervicocephalic kinesthesia compared to no treatment. Sensorimotor training approaches targeting proprioception, oculomotor control, and balance have produced sustained benefits over twelve months, including enhanced postural stability and decreased disability. The present study extends these findings to a smartphone-using population without established chronic pain, addressing the sensorimotor dysfunction at an earlier stage of the maladaptation continuum before it progresses to persistent pain syndromes.

Neurophysiological Interpretation

The constellation of improvements observed across proprioceptive, neuromuscular, and kinematic variables suggests a coordinated neurophysiological response to the multimodal sensorimotor intervention. Motor unit recruitment efficiency likely mediated the endurance gains through selective reactivation of low-threshold units in the deep cervical flexors, reversing the fatigue-induced recruitment substitution pattern. Afferent feedback restoration, driven by repeated proprioceptive challenge with sensor-augmented error correction, enhanced the gain of the cervical position-sense loop, enabling more precise error detection and correction during both clinical and functional tasks. Postural control adaptations emerged as an integrated outcome of these component improvements, reflecting cortical and subcortical reorganization of the sensorimotor networks governing cervico-scapular coordination during device interaction.

Limitations

Several limitations warrant consideration when interpreting these findings. The single-group pre–post design precludes causal attribution of improvements solely to the intervention, as natural history, placebo effects, regression to the mean, and participant expectation may have contributed to the observed changes. The absence of a control group and randomization limits the internal validity of the findings. The relatively small sample size of 24 participants, while adequately powered for the primary analysis, limits the generalisability of the results to broader populations. The six-week intervention period, though consistent with existing sensorimotor training protocols, does not permit evaluation of long-term retention of gains or the durability of behavioural modification. Additionally, the study population comprised predominantly young university students, and the findings may not translate directly to older adults or populations with different occupational smartphone usage patterns.

Clinical Implications

The findings of this study carry several important implications for physiotherapy clinical practice in the management of smartphone-induced musculoskeletal dysfunction. First, the substantial proprioceptive improvements observed following sensor-assisted repositioning training support the integration of quantified proprioceptive assessment and feedback-driven training into routine clinical evaluation of patients presenting with technology-related neck complaints. Cervical joint reposition error measurement using wearable inertial sensors provides an objective, reliable metric that can detect subclinical sensorimotor deficits missed by conventional photographic posture assessment and self-reported symptom scales.

Second, the significant restoration of deep cervical flexor endurance emphasises the importance of specifically targeting deep stabilizer recruitment in this population, rather than prescribing generalised cervical strengthening exercises that may reinforce existing compensatory patterns. The craniocervical flexion training protocol, with its emphasis on isolating deep flexor activation and monitoring sternocleidomastoid substitution, should be considered a foundational component of rehabilitation programmes for individuals with forward head posture secondary to habitual device use.

Third, the successful functional transfer of motor control gains to simulated smartphone use, as evidenced by reduced cervical flexion angles and time beyond threshold, demonstrates the value of incorporating task-specific retraining within the provocative activity itself. Clinicians should consider integrating real-time postural biofeedback during device interaction as a means of bridging the gap between clinical improvement and habitual behaviour modification, an outcome that conventional ergonomic advice alone has not reliably achieved.

Fourth, the multidimensional assessment framework employed in this study, encompassing proprioceptive, neuromuscular, electromyographic, kinematic, and functional measures, provides a template for comprehensive evaluation that captures the spectrum of cervico-scapular sensorimotor dysfunction. Clinicians are encouraged to move beyond single-variable assessment, such as craniovertebral angle alone, toward integrated sensorimotor profiling that guides targeted intervention prescription.

Finally, the prevention-oriented application of this intervention to habitual smartphone users without established chronic pain suggests a role for early sensorimotor screening and preemptive rehabilitation in populations at risk for technology-mediated musculoskeletal dysfunction. Given that the musculoskeletal consequences of smartphone overuse are projected to escalate with increasing device dependency across all age groups, proactive physiotherapy strategies that address sensorimotor dysfunction before it progresses to persistent pain syndromes represent a valuable public health contribution.

Conclusion

This pre–post experimental study demonstrated that a six-week sensor-based neuromuscular proprioceptive training programme produced significant improvements in craniovertebral angle, cervical joint reposition error, deep cervical flexor endurance, upper trapezius electromyographic activity, scapular dyskinesis, and functional cervical flexion behaviour during smartphone use in habitual users. The integration of wearable inertial sensor feedback with motor control-oriented rehabilitation addressed the sensorimotor substrate of cervico-scapular dysfunction rather than its symptomatic or postural manifestation alone. Future randomized controlled trials with larger sample sizes, active comparator groups, and extended follow-up periods are warranted to confirm these preliminary findings and establish the optimal dosage and long-term durability of sensor-assisted neuromuscular proprioceptive training for smartphone-induced musculoskeletal dysfunction.

References

1. Purushothaman V, Ramalingam V, Xian RWY, et al. The relationship between smartphone usage pattern and cervical proprioception in adults with text neck syndrome. Natl J Community Med. 2023;14(12):831–836.

2. Ha SY, Sung YH. A temporary forward head posture decreases function of cervical proprioception. J Exerc Rehabil. 2020;16(2):168–174.

3. Mohsen TMA, Badawy MS, Shendy W, et al. Effect of eye-cervical proprioceptive training program on cervical sensorimotor control dysfunction. Int J Educ Stud. 2025;11(22s):1075–1088.

4. Prakash SJ, Govindaraj A. Correlation between cervical posture and cervical proprioception among chronic smartphone users. Int J Physiother. 2024;11(3):67–72.

5. Kong YS, Kim YM, Shim JM. The effect of modified cervical exercise on smartphone users with forward head posture. J Phys Ther Sci. 2017;29(2):328–331.

6. Zhang Y, Liu L, et al. Exercise therapy to improve cervical proprioception in individuals with forward head posture: a systematic review. PLoS One. 2025;20(9):e0330665.

7. Pashine AA, Jethani S, Chourasia S. Does smartphone use really impact cervical rotation and cervical proprioception in asymptomatic individuals? Cureus. 2023;15(4):e37170.

8. Torkamani MH, Mokhtarinia HR, Vahedi M, Gabel CP. Relationships between cervical sagittal posture, muscle endurance, joint position sense, range of motion and level of smartphone addiction. BMC Musculoskelet Disord. 2023;24:61.

9. Jung M, Zind A, Ernst MJ. A new test protocol and device for measuring the cranio-cervical flexion test in participants with bruxism. Arch Physiother. 2025;15:138–147.

10. Lee SH, Son SJ. Effect of scapular stabilization exercise on neck alignment and muscles in patients with forward head posture. J Phys Ther Sci. 2018;30(6):869–874.

11. Wang J, Wang R, Zhao P, et al. The reliability and validity of a novel wearable inertial sensor to measure the cervical proprioception. Med Eng Phys. 2024;125:104125.

12. Bocos-Corredor E, Moggioli F, Pérez-Fernández T, et al. Reliability and usability of a novel inertial sensor-based system to test craniocervical flexion movement control. J Neuroeng Rehabil. 2024;21:170.

13. Zibari LY, et al. Effectiveness of sensorimotor training on pain, cervical joint position sense, range of motion, balance, and disability in chronic neck

pain: a systematic review. Heliyon. 2025;11(4):e43409.

14. Luznik I, Pajek M, Sember V, Majcen Rosker Z. The effectiveness of cervical sensorimotor control training for the management of chronic neck pain: a systematic review and meta-analysis. Montenegro J Sports Sci Med. 2025;14(1):91–104.

15. Ozer Kaya D, Toprak Celenay S. Association of smartphone overuse and neck pain: a meta-analysis. Postgrad Med J. 2025;101(1197):620–628.

16. Phuyal N, Pandey N, Pandeya A, Mishra AK. Smartphone overuse and its impact on musculoskeletal pain in the neck and wrists/hands in medical and nursing undergraduate students. Sci Rep. 2025;15:44945.

17. Kim YG, Kang MH, Kim SY, et al. Influence of the duration of smartphone usage on flexion angles of the cervical and lumbar spine and on reposition error in the cervical spine. Phys Ther Korea. 2013;20(1):10–17.

18. Alghadir AH, Gabr SA, Rizk AA, et al. Smartphone addiction and musculoskeletal associated disorders in university students: biomechanical measures and questionnaire survey analysis. Eur J Med Res. 2025;30:274.

19. Jung SH, Ha SW. Deep neck flexor endurance in university students: normative data and reliability. Phys Ther Rehabil Sci. 2018;7(4):186–190.

20. Hidalgo-Perez A, et al. Adding motor imagery to motor control training can improve neck sensorimotor function. Pain. 2021;162(12):2831–2840.

21. Bertozzi L, et al. Effectiveness and optimal dosage of exercise training for chronic non-specific neck pain. Clin Rehabil. 2020;34(6):774–782.

22. De Mey K, Danneels L, Cagnie B, et al. Conscious correction of scapular orientation in overhead athletes performing selected shoulder rehabilitation exercises. J Orthop Sports Phys Ther. 2013;43(1):3–10.

23. Paul M, et al. Effectiveness of motor control therapeutic exercise and proprioceptive neuromuscular facilitation in cervical spondylosis. Int J Physiother Res. 2020;8(5):3620–3627.

24. Physiopedia. Sensorimotor impairment in neck pain. Available from: https://www.physio-pedia.com/Sensorimotor_Impairment_in_Neck_Pain.

25. Physiopedia. Scapular dyskinesia. Available from: https://www.physio-pedia.com/Scapular_Dyskinesia.

26. Labib DH, AbdElmaged SF, Hassanien HR, et al. Correlation between forward head posture and myogenic temporomandibular disorder in addicted smartphone users. Front Health Inform. 2024;13(3):8015–8030.

27. Torkamani MH, et al. The association between mobile phone usage duration, neck muscle endurance, and neck pain in university students. Sci Rep. 2024;14:20218.

28. Falla D, Jull G, Hodges PW. Feedforward activity of the cervical flexor muscles during voluntary arm movements is delayed in chronic neck pain. Exp Brain Res. 2004;157(1):43–48.

29. Jull GA, O'Leary SP, Falla DL. Clinical assessment of the deep cervical flexor muscles: the craniocervical flexion test. J Manipulative Physiol Ther. 2008;31(7):525–533.

30. Sarig Bahat H, Takasaki H, Chen X, et al. Cervical kinematic training with and without interactive VR training for chronic neck pain: a randomized clinical trial. Man Ther. 2015;20(1):68–78.