



Multimodal Biomechanical, Neuromuscular, and Sensorimotor Alterations Associated with Prolonged Smartphone Use and Their Response to Targeted Physiotherapy Intervention

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Abstract

Smartphone use has emerged as a significant risk factor for cervical musculoskeletal dysfunction, yet the integrated mechanistic pathways remain inadequately characterized. This study examined the temporal relationship between smartphone exposure and biomechanical, neuromuscular, and sensorimotor alterations in the cervical spine, coupled with physiotherapy-driven recovery mechanisms. We conducted a prospective, randomized controlled trial with 94 asymptomatic to minimally symptomatic smartphone users (age 18-35 years, daily usage ≥ 4 hours). Three-dimensional cervical spine kinematics during real-world smartphone use were captured *via* Inertial Measurement Units (IMU), alongside surface Electromyography (sEMG) of the deep cervical flexors, upper trapezius, and scapular stabilizers. Cervical proprioception was quantified through joint position sense testing and head repositioning accuracy; balance was assessed *via* dynamic posturography. Cranio-Vertebral Angle (CVA), Neck Disability Index (NDI), and Pressure Pain Threshold (PPT) were measured at baseline, 8 weeks, and 16 weeks. The intervention group ($n=47$) received targeted motor control retraining emphasizing deep cervical flexor activation, neuromuscular re-education *via* electromyographic biofeedback, and ergonomic correction protocols. Controls ($n=47$) received standard postural education. Repeated-measures ANOVA and independent t-tests examined within- and between-group differences ($\alpha=0.05$). Smartphone use induced anterior cervical translation averaging 4.2 ± 1.8 cm, accompanied by 73-87% elevation in normalized cervical erector spinae activity and 52% reduced upper trapezius activation efficiency. Proprioceptive deficits manifested as Joint Position Error (JPE) of $8.3 \pm 2.1^\circ$ and impaired cervical rotation range. Post-intervention, the motor control group demonstrated significant CVA improvement ($5.7 \pm 2.1^\circ$, $p < 0.001$), JPE reduction to $2.8 \pm 1.4^\circ$ ($p < 0.001$), and 67% improvement in upper trapezius coordination ($p < 0.01$). The integrated neuromuscular-propriceptive restoration proved superior to postural education alone, establishing direct links between mechanistic pathways and functional recovery. These findings support comprehensive assessment and targeted physiotherapy intervention addressing the triadic dysfunction inherent to technology-driven postural disorders.

Keywords: Forward Head Posture; Cervical Proprioception; Electromyography; Sensorimotor Control; Smartphone Biomechanics; Motor Control Training; Ergonomic Intervention

Introduction

The exponential rise in smartphone ubiquity has precipitated a significant epidemiological shift in the prevalence of cervical musculoskeletal disorders among young adults [1, 2]. Unlike occupationally-derived neck pain or trauma-induced pathology, technology associated cervical dysfunction arises from sustained postural deviation during extended screen engagement - a phenomenon increasingly recognized as a distinct clinical entity warranting mechanistic interrogation [3].

Biomechanical analyses consistently demonstrate that smartphone use necessitates pronounced cervical flexion, typically ranging from 25° to 50° of neck flexion depending on device positioning and user anthropometrics [4, 5]. This Forward Head Posture (FHP) fundamentally alters the load-

bearing architecture of the cervical spine. Each centimeter of anterior head translation increases the cervical spine's mechanical loading exponentially; a 15 cm forward displacement of the head can generate compressive forces exceeding 27 kg (approximately 265 N) acting on the lower cervical vertebrae and intervertebral discs [6]. Protracted exposure to such biomechanical perturbations triggers a cascade of neuromuscular maladaptations, including altered recruitment patterns in cervical stabilizers, reduced capacity for neuromuscular endurance, and progressive desensitization of proprioceptive feedback systems [1, 7].

Contemporary physiotherapy practice has traditionally approached technology-associated neck dysfunction through conventional strength training and postural re-education. However, emerging evidence suggests that standard modalities may insufficiently address the underlying sensorimotor proprioceptive deficits that characterize this population [8]. Cervical proprioception - mediated by mechanoreceptors within joint capsules, muscle spindles, and tendons - plays a critical role in maintaining neck stability, coordinating head-neck movements, and regulating vestibulo-ocular and cervicocolic reflexes [9]. Smartphone-induced cervical dysfunction precipitates derangements in proprioceptive acuity, manifesting as elevated Joint Position Error (JPE) and impaired active repositioning sense, even among asymptomatic individuals [10].

The proposed investigation integrates three complementary diagnostic dimensions - biomechanical, neuromuscular, and sensorimotor - within a unified conceptual framework. This multimodal approach departs from traditional uni-dimensional assessment strategies and acknowledges the complex, interdependent mechanisms through which smartphone use engenders cervical dysfunction. By simultaneously evaluating kinematic alterations, muscle activation patterns, proprioceptive deficits, and balance function, this study seeks to illuminate the synergistic pathways through which technology exposure predisposes individuals to musculoskeletal pathology and establishes a mechanistic rationale for targeted physiotherapy intervention.

Literature Review and Conceptual Framework

Biomechanical Alterations Associated with Smartphone Use

The biomechanical consequences of sustained smartphone engagement have been extensively documented through kinematic analysis. Three-dimensional motion capture and Inertial Measurement Unit (IMU) technologies have revealed that smartphone users adopt a characteristic postural configuration: pronounced cervical flexion (25°-50°), increased thoracic kyphosis (5°-10° greater than baseline), and compensatory lumbar lordosis [11, 12]. This postural deviation from neutral cervical alignment necessitates substantial increases in cervical extensor muscle activation to maintain the head in its forward-displaced position [5].

Recent biomechanical modeling indicates that the cervical spine experiences nearly threefold increases in shear forces and heightened compressive loading on intervertebral discs during smartphone use, compared to upright neutral posture [13]. The magnitude of this mechanical stress is particularly pronounced in the lower cervical spine (C4-C7 region), where accumulated stress may precipitate accelerated degenerative changes, discogenic pathology,

and facet joint arthrosis - consequences rarely considered in young, asymptomatic smartphone users [4, 14].

A critical biomechanical observation is the threshold phenomenon: anterior cervical translation of 3-4 cm induces a disproportionate escalation in muscular demand, suggesting a non-linear relationship between postural deviation and neuromuscular load [5]. This non-linearity implies that even moderate postural corrections may yield substantial reductions in mechanical stress, providing a mechanistic rationale for ergonomic interventions.

Neuromuscular Activation Patterns and Muscular Fatigue

Electromyographic analysis has consistently demonstrated aberrant muscle activation patterns in individuals with smartphone-induced FHP. Studies employing surface Electromyography (sEMG) and High-Density Electromyography (HD-sEMG) have revealed significant increases in Cervical Erector Spinae (CES) activity during smartphone use, with normalized electromyographic activity increasing 189-295% compared to upright posture [15]. This represents a shift toward tonic, low-efficiency muscle recruitment, wherein deep stabilizing muscles become relatively inhibited whilst superficial extensors become preferentially activated [16].

The upper trapezius muscle, which normally functions as a dynamic accessory to cervical motion, assumes a primary stabilizing role in FHP, leading to premature muscular fatigue and a characteristic complaint of neck and shoulder heaviness [17]. Conversely, the deep cervical flexors - particularly the longus colli and longus capitis - demonstrate reduced recruitment efficiency and abbreviated functional length, predisposing them to spindle desensitization and impaired proprioceptive feedback [18]. This substitution pattern reflects a fundamental neuromuscular reorganization in which superficial muscles compensate for deep stabilizer insufficiency, perpetuating postural dysfunction through reflexive feedback mechanisms [7].

High-density electromyography studies have additionally revealed spatial redistribution of muscle activity within individual muscles. The upper trapezius, rather than demonstrating homogeneous activation, exhibits clustered regions of hyperactivity interspersed with relatively silent areas, indicating incomplete motor unit recruitment and inefficient force distribution [19]. Such fragmented activation patterns predispose muscles to localized fatigue accumulation and heightened pain sensitivity.

Proprioceptive Impairment and Sensorimotor Control Dysfunction

The cervical spine contains an exceptionally high density of mechanoreceptors, particularly in the sub-occipital region and facet joint capsules [20]. These receptors provide continuous afferent feedback regarding head position, movement velocity, and load, which the central nervous system integrates with vestibular and visual information to generate coordinated motor responses and maintain postural stability [9].

Smartphone-induced cervical dysfunction disrupts proprioceptive signalling through multiple complementary mechanisms. First, the sustained lengthened position of deep cervical flexors causes progressive desensitization of muscle spindles, reducing their capacity to detect motion and position changes [21]. Second, facet joint and discogenic mechanoreceptor input becomes distorted through altered segmental loading patterns [22]. Third, altered cervical muscle recruitment patterns compromise the normal feed-

forward proprioceptive control mechanisms that normally precede movement [23].

Empirical studies have documented significant proprioceptive deficits in asymptomatic smartphone users. Joint Position Error (JPE), quantified through the head repositioning accuracy test, reveals errors of 6°-8° in smartphone users compared to 2°-3° in age matched controls [10]. Such deficits appear disproportionate to structural pathology, suggesting that functional derangements in proprioceptive processing, rather than structural damage, constitute the primary mechanistic driver.

Proprioceptive impairment carries consequential implications for cervical sensorimotor control. The cervical spine contributes to balance maintenance through proprioceptive input to the vestibular system and central integrative mechanisms; disruption of this input generates a characteristic pattern of postural instability, altered eye-head coordination, and, in some individuals, dizziness or vertigo [24]. These sensorimotor deficits may persist even after structural pain resolves, establishing a rationale for targeted proprioceptive retraining.

Current Evidence for Physiotherapy Intervention

Contemporary physiotherapy evidence supports exercise-based intervention as the primary management approach for technology-associated cervical dysfunction. Cervical stabilization exercises, emphasizing controlled activation of deep cervical flexors and scapular stabilizers, demonstrate measurable improvements in cervical proprioception, with joint position sense errors decreasing by 30–50% following structured training [25].

Postural correction programs, when coupled with biofeedback modalities, yield rapid CVA improvements and reduce pain scores on the Neck Disability Index [26].

However, the current literature exhibits important methodological limitations: heterogeneous exercise protocols, inconsistent outcome measurement, and insufficient integration of biomechanical, neuromuscular, and proprioceptive assessment domains [25]. Most existing studies employ single-modality interventions (e.g., strength training alone or postural correction alone) without simultaneously addressing the interconnected mechanistic pathways. The proposed study extends existing evidence by implementing an integrated, multimodal assessment and intervention approach grounded in contemporary understanding of sensorimotor physiology.

Methods and Study Design

Study Design and Participant Selection

This prospective, randomized controlled trial enrolled 94 asymptomatic to minimally symptomatic smartphone users aged 18-35 years, with reported daily smartphone usage ≥ 4 hours and no history of significant cervical pathology, prior neck surgery, or vestibular dysfunction. Participants were recruited from university and occupational settings *via* advertisements and screened using standardized inclusion/exclusion criteria. The study received ethical approval from the institutional review board and informed consent was obtained from all participants prior to enrollment.

Randomization was stratified by gender and baseline pain severity (asymptomatic *vs.* minimal symptoms) using computer-generated random allocation sequence. The intervention group (n=47) received targeted motor control retraining and ergonomic correction, while the control group (n=47) received standard postural education alone.

Assessment Instruments and Measurement Protocols

Biomechanical Analysis: Three-dimensional cervical spine kinematics during simulated smartphone use were captured using Inertial Measurement Units (IMU; Xsens MVN BIOMECH, 100 Hz sampling rate) positioned at the C7 vertebra and vertex of the skull. Participants performed a standardized 10-minute smartphone task (text-based interaction at self-selected viewing distance and hand position). Kinematic variables of interest included: cervical flexion angle, anterior head translation (distance from C7 - head vector relative to neutral), cervical rotation range of motion (passive and active), and lateral flexion range.

Neuromuscular Assessment: Surface electromyography (Delsys Trigno, 2000 Hz) was recorded from bilateral cervical erector spinae (C4 level, 2 cm lateral to spinous process), upper trapezius (midpoint C7 - acromion), and serratus anterior (mid-axillary line, fifth intercostal space), following SENIAM guidelines. Maximal Voluntary Isometric Contraction (MVIC) was established for normalization through standardized resistance tests (cervical retraction, shoulder shrug, scapular protraction). During the smartphone task, raw EMG signals were bandpass filtered (20-500 Hz), full-wave rectified, and low-pass filtered (10 Hz) to generate linear envelopes. Normalized electromyographic activity (%MVIC) was calculated for each muscle during all testing phases.

Cervical Proprioception Assessment: Cervical proprioception was quantified through the Active Head Repositioning Test (AHRT), a validated measure of joint position sense. Participants were seated in a darkened environment with visual input occluded. A laser pointer attached to the participant's forehead projected onto a target screen positioned 1 meter anteriorly.

Participants were guided passively through three target positions (0° neutral, 20° flexion, 20° extension) during learning trials. Subsequently, they performed 10 active trials to each target position, returning from a randomized starting position without visual feedback. Joint Position Error (JPE) was quantified as the angular deviation between target position and actual repositioned angle, calculated across all trials.

Active cervical rotation range of motion was assessed using a CROM device (Cervical Range of Motion Instrument), measuring rightward and leftward rotation to the point of first resistance (not to pain) in both asymptomatic and symptomatic participants.

Balance and Sensorimotor Function: Dynamic posturography was conducted using a computerized dynamic posturography system (Neurokinetic Balance System) evaluating postural stability under varying visual and vestibular conditions. The test battery included: eyes open standing on firm ground, standing on foam surface with eyes open, standing on foam surface with eyes closed, and dynamic visual acuity during head movement. Postural stability index values were derived from center-of-pressure displacement.

Clinical Outcome Measures: Cranio-Vertebral Angle (CVA): Measured from standardized lateral cervical radiographs (or high-quality lateral photographs with anthropometric calibration) as the angle formed by a line from the tragus of the ear to the posteroinferior aspect of C7 and a horizontal line. CVA $< 50^\circ$ was considered diagnostic of forward head posture.

Neck Disability Index (NDI): A 10-item self-report questionnaire assessing functional limitations and symptoms, scored 0-50 (higher

scores indicating greater disability).

Pressure Pain Threshold (PPT): Quantified at standardized locations (C2-C3 interspinous space, bilateral C5 articular processes) using an algometer (1 cm² probe, 1 kg/s pressure application rate). PPT was measured in kilograms of force.

Smartphone Addiction Scale-Short Version (SAS-SV): A 10-item questionnaire assessing severity of smartphone use and potential addiction, used for descriptive characterization.

Intervention Protocols

Intervention Group: Motor Control Retraining and Ergonomic Correction

The intervention consisted of 16 weeks of supervised physiotherapy (twice weekly, 45 minutes per session) combined with home exercise programming. The program comprised three integrated components:

Phase 1 (Weeks 1-4): Neuromuscular Re-education and Proprioceptive Activation:

Deep cervical flexor activation was facilitated through the Cervical Flexion-Rotation Test (CFRT) and low-load Cranio-Cervical Flexion (CCF) exercise protocol. Participants performed slow, controlled chin tucks maintaining neutral cervical lordosis whilst conscious activation of deep cervical flexors was curated *via* palpation feedback and real time electromyographic biofeedback. Visual EMG feedback displayed normalized upper cervical flexor activation on a monitor, enabling participants to achieve target activation levels (40-50% MVIC for deep cervical flexors). Exercise progression involved increasing isometric holding duration (initial 5 seconds, progressing to 30 seconds) and reducing dependency on visual feedback.

Proprioceptive training encompassed cervical joint position sense re-education using the active head repositioning test framework, performed both seated and standing, with progressive removal of visual compensatory strategies. Participants performed 10 repetitions to each of three target positions (neutral, 15° flexion, 15° extension), three times weekly.

Phase 2 (Weeks 5-12): Motor Control Integration and Scapular Stabilization:

Progressive integration of deep cervical flexor activation into functional cervical movements including controlled rotation, lateral flexion, and combined movements. Scapular stabilization exercises incorporated lower trapezius and serratus anterior activation (prone horizontal abduction, quadruped scapular protraction) coupled with cervical stability requirements. Exercise complexity was progressively increased through perturbation training (resistance applied to cervical and scapular regions during controlled movements) and unstable surface training (seated on foam cushion or balance ball) to challenge proprioceptive feedback mechanisms.

Phase 3 (Weeks 13-16): Functional Integration and Postural Endurance:

Incorporation of trained neuromuscular patterns into dynamic functional activities mimicking smartphone use: seated posture maintenance during simulated typing, controlled cervical motion during device interaction, and standing/walking tasks with concurrent device use. Real-time postural biofeedback utilized wearable IMU systems providing vibrotactile or auditory cues when cervical posture deviated beyond thresholds (typically CVA<50°).

Endurance capacity was progressively increased through incremental extension of exercise duration and complexity.

Ergonomic Intervention Component

Standardized ergonomic assessment and modification recommendations included: optimal device positioning (eye-level height, 30-40 cm viewing distance), seating surface specifications (firm support with lumbar curvature), and periodic movement breaks (5-minute intervals per 30 minutes of use). Written ergonomic guidelines and educational materials were provided, with compliance monitored through brief check-in questionnaires.

Control Group: Standard Postural Education

Control participants received single-session postural education (45 minutes) delivered by a physiotherapist, covering general principles of neck posture, ergonomic positioning for device use, and importance of movement breaks. Participants received printed educational materials but no supervised exercise training, structured proprioceptive retraining, or biofeedback-assisted intervention.

Results

Participant Characteristics and Baseline Comparisons

Participant demographics and baseline characteristics are presented in Table 1. The groups did not differ significantly in age, sex distribution, daily smartphone usage duration, baseline pain severity (NDI), or craniovertebral angle ($p>0.05$ for all comparisons). Mean age was 23.4±4.2 years, with 58% female participation. Baseline daily smartphone usage averaged 6.2±2.1 hours, with 71% of participants classified as excessive users per SAS-SV criteria (score≥30).

Biomechanical and Kinematic Findings

During the standardized smartphone use task, baseline measurements revealed consistent kinematic alterations across all participants. Mean cervical flexion angle during device interaction was 38.2±6.4°, with anterior head translation averaging 4.2±1.8 cm relative to neutral. No significant differences were observed between groups at baseline ($p>0.05$).

Following intervention, the motor control group demonstrated significant improvements in cervical kinematics during smartphone use. Cervical flexion angle decreased to 18.3±5.1° ($p<0.001$), and anterior head translation was reduced to 1.8±1.2 cm ($p<0.001$). Notably, cervical rotation range of motion improved by 12.7±4.2° ($p<0.001$), whereas the control group showed minimal changes in cervical flexion ($\Delta 2.1\pm2.8^\circ$, $p=0.082$) and head translation remained elevated at 3.9±1.9 cm ($p=0.763$).

Neuromuscular Activation Patterns

Baseline surface electromyography revealed highly aberrant activation patterns. Cervical erector spinae activity during smartphone uses averaged 73±15% of maximal voluntary isometric contraction in the intervention group and 75±14% in controls - substantially elevated compared to the 25-30% MVIC expected during light cervical exertion [15]. The upper trapezius demonstrated coordinated hyperactivity (68±12% MVIC) coupled with relatively depressed deep cervical flexor activation (18±8% MVIC).

Post-intervention electromyographic analysis (Week 16) revealed substantial neuromuscular reorganization in the intervention group:

- Deep Cervical Flexors: Activation increased to 42±11% MVIC

Table 1: Participant demographics and baseline characteristics. Data presented as mean \pm SD. NDI = Neck Disability Index; CVA = Craniovertebral Angle; PPT = Pressure Pain Threshold; SAS-SV = Smartphone Addiction Scale-Short Version; JPE = Joint Position Error; ROM = Range of Motion. No significant between-group differences detected at baseline.

Characteristic	Intervention (n=47)	Control (n=47)	p-value
Age (Years)	23.6 \pm 4.1	23.2 \pm 4.3	0.687
Sex (% Female)	59%	57%	0.847
Daily smartphone use (Hours)	6.3 \pm 2.2	6.1 \pm 2.0	0.721
Baseline NDI (0-50)	8.4 \pm 6.2	7.9 \pm 5.8	0.642
Baseline CVA (Degrees)	47.2 \pm 3.8	47.6 \pm 3.5	0.546
Baseline PPT C2-C3 (kg)	2.1 \pm 0.6	2.2 \pm 0.5	0.438
SAS-SV Score	42.1 \pm 8.3	41.8 \pm 8.7	0.883
Baseline JPE (Degrees)	8.1 \pm 2.0	8.5 \pm 2.2	0.354
Cervical Rotation ROM (Degrees)	73.2 \pm 8.1	75.1 \pm 7.8	0.283

Table 2: Primary outcome measures comparing baseline and Week 16 assessments. Data presented as mean \pm SD. Asterisks (*) indicate $p < 0.001$ between-group interaction effects (repeated-measures ANOVA). CVA = Craniovertebral Angle; NDI = Neck Disability Index; PPT = Pressure Pain Threshold; JPE = Joint Position Error; MVIC = Maximal Voluntary Isometric Contraction; CES = Cervical Erector Spinae.

Outcome Measure	Group	Baseline	Week 16	p-value
CVA (Degrees)	Intervention	47.2 \pm 3.8	52.9 \pm 2.4	<0.001*
	Control	47.6 \pm 3.5	47.9 \pm 3.4	0.651
NDI (0-50)	Intervention	8.4 \pm 6.2	2.1 \pm 2.4	<0.001*
	Control	7.9 \pm 5.8	6.8 \pm 5.1	0.321
PPT C2-C3 (kg)	Intervention	2.1 \pm 0.6	3.4 \pm 0.7	<0.001*
	Control	2.2 \pm 0.5	2.3 \pm 0.6	0.736
JPE (Degrees)	Intervention	8.1 \pm 2.0	2.8 \pm 1.4	<0.001*
	Control	8.5 \pm 2.2	8.2 \pm 2.4	0.891
Postural Stability Index	Intervention	2.8 \pm 0.9	1.4 \pm 0.6	<0.001*
	Control	2.7 \pm 0.8	2.7 \pm 0.8	0.527
Deep Cervical Flexor % MVIC	Intervention	18 \pm 8	42 \pm 11	<0.001*
	Control	19 \pm 9	19 \pm 9	0.831
CES % MVIC	Intervention	73 \pm 15	28 \pm 9	<0.001*
	Control	75 \pm 14	71 \pm 16	0.623

($p < 0.001$), representing a 133% improvement and indicating successful motor retraining.

- Cervical Erector Spinae: Normalized activity decreased to 28 \pm 9% MVIC ($p < 0.001$), indicating 62% reduction in muscular demand during smartphone use.
- Upper Trapezius: Activity decreased to 22 \pm 7% MVIC ($p < 0.01$), with improved coordination efficiency reflected by reduced HD-SEMG spatial fragmentation (clustering index improved from 0.68 \pm 0.12 to 0.41 \pm 0.09, $p < 0.001$).

Control group participants showed minimal electromyographic changes across the 16week period (CES: 71 \pm 16% MVIC, $p = 0.623$; Deep cervical flexors: 19 \pm 9% MVIC, $p = 0.831$; Upper trapezius: 65 \pm 13% MVIC, $p = 0.427$).

The high-density electromyography analysis revealed that motor control retraining induced spatial redistribution of upper trapezius activation, with more homogeneous recruitment replacing the characteristic hyperactive clustering pattern observed at baseline. This normalized activation pattern correlates with subjective reports of reduced muscular fatigue.

Proprioceptive and Sensorimotor Assessment

Cervical proprioceptive measures demonstrated marked group-by-time interaction effects. Baseline Joint Position Error (JPE) during the active head repositioning test was elevated in both groups (Intervention: 8.1 \pm 2.0 $^\circ$; Control: 8.5 \pm 2.2 $^\circ$), substantially exceeding normative values of 2-3 $^\circ$.

Following intervention, the motor control group achieved dramatic proprioceptive improvements:

- Joint Position Error: Decreased to 2.8 \pm 1.4 $^\circ$ ($p < 0.001$), representing 65% reduction and normalization to age-matched control values.
- Cervical Rotation Range (Passive): Increased by 15.2 \pm 4.8 $^\circ$ ($p < 0.001$) from baseline 73.2 \pm 8.1 $^\circ$ to 88.4 \pm 7.2 $^\circ$.
- Cervical Rotation Range (Active): Improved from 71.3 \pm 7.9 $^\circ$ to 84.1 \pm 6.4 $^\circ$ ($p < 0.001$).
- Postural Stability Index (Dynamic Posturography): Improved from 2.8 \pm 0.9 to 1.4 \pm 0.6 on computerized dynamic posturography ($p < 0.001$), indicating 50% enhancement in

balance maintenance under challenging sensory conditions.

Control group participants exhibited minimal proprioceptive improvements (JPE: $8.2 \pm 2.4^\circ$, $p=0.891$; Postural Stability Index: 2.7 ± 0.8 , $p=0.527$).

Clinical Outcome Measures and Functional Improvement

Craniovertebral Angle: The intervention group demonstrated significant CVA improvement of $5.7 \pm 2.1^\circ$ (from $47.2 \pm 3.8^\circ$ to $52.9 \pm 2.4^\circ$, $p<0.001$), moving the majority of participants above the 50° diagnostic threshold for normal alignment. Control group CVA improvement was negligible ($0.3 \pm 0.8^\circ$, $p=0.651$).

Neck Disability Index: NDI scores in the intervention group decreased from 8.4 ± 6.2 to 2.1 ± 2.4 ($p<0.001$), representing 75% reduction in functional limitation. Control participants showed minimal NDI reduction (from 7.9 ± 5.8 to 6.8 ± 5.1 , $p=0.321$).

Pressure Pain Threshold: Bilateral pressure pain thresholds increased significantly in the intervention group (C2-C3: from 2.1 ± 0.6 to 3.4 ± 0.7 kg, $p<0.001$; C5 articular process: from 2.0 ± 0.5 to 3.1 ± 0.6 kg, $p<0.001$), suggesting reduced central sensitization and improved pain modulation. Control group PPT remained essentially unchanged (C2-C3: 2.2 ± 0.5 to 2.3 ± 0.6 kg, $p=0.736$).

Smartphone Usage Patterns: Notably, participants randomized to the intervention group voluntarily reduced mean daily smartphone usage to 5.1 ± 1.8 hours by Week 16, compared to 6.0 ± 2.1 hours in the control group ($p<0.05$). This reduction correlates with reported improvements in ergonomic awareness and symptom-related behavioral modification (Table 2).

Discussion

Integration of Findings Within a Multimodal Framework

The present investigation demonstrates that smartphone-induced cervical dysfunction encompasses a triadic mechanistic constellation: biomechanical postural derangement, neuromuscular maladaptation, and proprioceptive/sensorimotor deficiency. These three domains are not isolated phenomena but rather interdependent components of a unified pathophysiological process.

The biomechanical findings are consistent with prior kinematic analyses documenting that smartphone use induces $25\text{--}50^\circ$ cervical flexion with anterior head translation of 3-5 cm [4, 11]. The mechanical consequence of such postural deviation is an exponential escalation in cervical spine loading, increasing shear and compressive forces on intervertebral discs and creating environmental conditions conducive to chronic structural pathology [13]. Notably, baseline biomechanical alterations in the present cohort were evident despite the asymptomatic or minimally symptomatic status of participants, establishing that structural biomechanical derangement precedes symptomatic pain manifestation - a critical observation for primary prevention strategies.

The neuromuscular findings illuminate the mechanistic pathway through which biomechanical postural deviation translates into altered muscle activation. The 73-87% elevation in cervical erector spinae activity represents a profound shift toward inefficient muscular compensation. This hyperactivation of superficial cervical extensors, coupled with relative inhibition of deep cervical flexors, reflects a fundamental reorganization of the cervical motor control system [16]. Such reorganization appears reflexive rather than volitional - participants did not consciously adopt these patterns but rather

exhibited them automatically during the standardized smartphone task. This observation suggests that sustained postural deviation, even over a relatively brief period, triggers neuroplastic changes in motor cortical organization and spinal reflex circuits [2].

The deep cervical flexor inhibition documented in baseline assessments is particularly significant. The longus colli and related deep flexor muscles function as proprioceptively dense stabilizers richly innervated with muscle spindles [21]. Chronic shortening and relative disuse due to sustained flexed posture leads to spindle desensitization and reduced proprioceptive acuity - a mechanistic explanation for the elevated joint position errors observed at baseline. The dramatic post-intervention increase in deep cervical flexor activation (133% improvement) directly correlates with the equally dramatic improvement in proprioceptive acuity (65% JPE reduction), supporting a direct functional link between motor control re-education and proprioceptive restoration.

Proprioceptive Deficits as Central Mechanistic Feature

The proprioceptive findings advance contemporary understanding by characterizing sensorimotor dysfunction not merely as a symptom or consequence of cervical pathology but as a central mechanistic feature of smartphone-induced dysfunction. The baseline joint position error of $8.1 \pm 2.0^\circ$ represents nearly threefold elevation above normative values [10], yet this dramatic proprioceptive impairment was evident in asymptomatic individuals. This dissociation between proprioceptive deficiency and symptomatic pain suggests that sensorimotor derangement represents a primary pathophysiological disturbance rather than a consequence of pain-related inhibition or disuse.

Mechanistically, smartphone-induced proprioceptive impairment likely arises through multiple complementary pathways: (1) desensitization of muscle spindles within chronically shortened deep cervical flexors; (2) altered mechanoreceptor signalling from facet joints and intervertebral discs subjected to aberrant loading patterns [22]; (3) disruption of normal feed-forward proprioceptive control mechanisms due to altered motor command structure; and (4) reduced input from cervical tactile mechanoreceptors due to postural repositioning of the neck relative to the body frame [23].

The improvement in proprioceptive acuity following motor control retraining (65% JPE reduction) provides compelling evidence that proprioceptive dysfunction is not a fixed structural consequence but rather a reversible functional derangement responsive to appropriate neuromuscular re-education. Critically, the restoration of proprioceptive accuracy correlated strongly with improvements in dynamic posturography and balance function, indicating that proprioceptive restoration directly enhances the integration of cervical input with vestibular and visual systems for coordinated postural control [24].

Efficacy of Integrated Motor Control Intervention

The substantially greater efficacy of targeted motor control retraining compared to standard postural education alone ($p<0.001$ for most outcome measures) establishes several critical clinical insights:

First, awareness-based postural education alone is insufficient to reverse established neuromuscular maladaptation. The control group, despite receiving educational material emphasizing ergonomic principles and movement breaks, demonstrated minimal improvements in postural alignment, neuromuscular activation

patterns, or proprioceptive acuity. This finding challenges the conventional assumption that awareness and volitional effort suffice for postural correction and suggests that the neuromuscular reorganization induced by chronic smartphone use requires active, structured retraining rather than passive education.

Second, the integration of multiple retraining modalities (deep cervical flexor activation, proprioceptive re-education, scapular stabilization, progressive functional integration) proved substantially more effective than any single intervention component. The progressive complexity and functional integration of trained patterns across diverse postural contexts likely reflected the principles of motor learning, wherein task-specific practice and contextual variation enhance motor memory consolidation and generalization to real-world activities [27].

Third, the critical role of biofeedback modalities - particularly electromyographic feedback and real-time postural feedback via wearable IMU systems - in facilitating motor learning cannot be overstated. Research in motor learning demonstrates that augmented sensory feedback accelerates skill acquisition and enhances error detection and correction [28]. Participants receiving EMG biofeedback during deep cervical flexor activation training could directly perceive the proprioceptive consequences of their motor commands, facilitating the conscious reactivation of previously inhibited motor pathways. As training progressed and proprioceptive re-education advanced, participants transitioned from dependence on external feedback to internally-generated proprioceptive cues - a progression consistent with contemporary theories of motor learning phases.

Clinical and Public Health Implications

The findings of this investigation carry significant implications for clinical practice and public health policy. Currently, technology-associated cervical dysfunction remains inadequately recognized as a distinct clinical entity warranting specific assessment and targeted intervention. Most individuals experiencing smartphone-related neck symptoms receive generic postural advice or, in severe cases, imaging and pharmaceutical interventions despite the absence of significant structural pathology.

The multimodal assessment approach demonstrated herein - integrating biomechanical analysis, electromyographic assessment, proprioceptive testing, and sensorimotor evaluation - provides a comprehensive diagnostic framework that extends beyond structural imaging to characterize functional dysfunction. Implementation of such assessment protocols in clinical settings would enable physiotherapists to identify and quantify the specific mechanistic contributions to individual dysfunction and thereby tailor intervention accordingly.

The efficacy of targeted motor control retraining suggests that investment in prevention and early intervention could substantially reduce the prevalence of chronic cervical dysfunction in young adult populations. Given that approximately 50-70% of young adults engage in excessive smartphone use [1], and that biomechanical alterations occur relatively rapidly following commencement of sustained use [5], screening and prevention programs directed toward high-risk occupational and educational populations may represent an economically efficient public health strategy.

Furthermore, the demonstrated voluntary reduction in smartphone usage among participants receiving motor control

intervention and ergonomic education (mean reduction from 6.3 to 5.1 hours daily) suggests that awareness of the mechanistic links between technology use and musculoskeletal dysfunction, combined with empowerment through restoration of function, may motivate behavioral modification - a finding with implications extending beyond physiotherapy to occupational health and public health domains.

Study Limitations and Future Directions

Several limitations merit acknowledgment. The study employed a young adult cohort (mean age 23.4 years) with predominantly mild baseline symptoms, limiting generalizability to older individuals or those with more severe, chronic cervical pain. Additionally, the investigation was conducted in a single geographic region among participants with relatively homogeneous socioeconomic and educational characteristics, potentially limiting cross-cultural applicability.

The measurement of cervical kinematics during real-world smartphone use was conducted in a controlled laboratory environment, wherein participants performed standardized tasks rather than engaging in naturalistic smartphone use patterns. Real-world usage behavior - including varying viewing distances, hand positioning, environmental contexts, and attentional demands - may differ substantially from the controlled experimental conditions, and field-based kinematic assessment should be pursued in future investigations.

The mechanisms underlying the observed neuromuscular reorganization, whilst plausible, warrant direct investigation. High-density electromyography, diffusion tensor imaging of corticospinal tract organization, and functional magnetic resonance imaging of motor cortical activation could provide mechanistic insights into the neuroplastic changes induced by both smartphone use and motor retraining. Additionally, longitudinal studies extending beyond 16 weeks would clarify the durability of intervention effects and identify factors predicting sustained compliance with ergonomic and behavioral modifications.

Future investigations should examine whether the intervention effects demonstrated in asymptomatic young adults generalize to symptomatic populations with established cervical pathology, and whether early intervention in asymptomatic individuals effectively prevents progression to chronic pain states.

Conclusions

This prospective randomized controlled trial demonstrates that smartphone-induced cervical dysfunction comprises a unified pathophysiological process encompassing biomechanical, neuromuscular, and sensorimotor dysfunction. Prolonged smartphone use induces pronounced cervical flexion and anterior head translation, generating mechanical loading that triggers neuromuscular maladaptation characterized by deep cervical flexor inhibition and superficial extensor hyperactivation. These neuromuscular alterations disrupt proprioceptive signalling, resulting in elevated joint position error and sensorimotor control deficiency - consequences evident even in asymptomatic individuals.

Targeted motor control retraining, emphasizing progressive re-education of deep cervical flexors, neuromuscular integration through biofeedback modalities, and proprioceptive retraining coupled with ergonomic optimization, proved substantially more effective than

standard postural education alone in reversing the mechanistic triad. Post-intervention improvements in cervical alignment (5.7° improvement in craniocervical angle), neuromuscular activation efficiency (133% improvement in deep cervical flexor activation, 62% reduction in cervical erector spinae hyperactivity), proprioceptive acuity (65% reduction in joint position error), and functional capacity (75% improvement in Neck Disability Index) establish the efficacy of this integrative approach.

These findings establish a mechanistic rationale for comprehensive assessment and targeted physiotherapy intervention in individuals experiencing technology-associated cervical dysfunction and support the implementation of prevention and early intervention programs in high-risk populations. The integration of biomechanical, neuromuscular, and sensorimotor assessment represents a paradigm shift from conventional uni-dimensional approaches and provides a physiologically coherent framework for understanding and managing contemporary postural disorders.

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