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Smartphone Use and Altered Spinal Load Distribution During Dynamic Tasks: Implications for Lumbo-Pelvic Rhythm and Trunk Stabilization

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Abstract

Background: The exponential rise in smartphone usage has introduced sustained postural deviations characterized by cervical flexion and thoracic kyphosis. While static postural consequences are well-documented, the biomechanical impact on dynamic spinal load distribution during functional movement tasks remains inadequately investigated. Habitual smartphone postures may fundamentally alter neuromuscular control strategies and segmental load transfer across the kinetic chain during activities requiring coordinated trunk motion.

Objective: This study aimed to determine whether habitual smartphone use alters spinal load distribution patterns and lumbo-pelvic rhythm during dynamic functional tasks, and to evaluate the effectiveness of movement re-patterning interventions on restoring optimal trunk control mechanisms.

Methods: Fifty-four adults aged 18-30 years were allocated into two groups based on daily smartphone usage: heavy users (>4 hours/day, n=27) and low users (<1 hour/day, n=27). Participants underwent comprehensive biomechanical assessment including lumbo-pelvic rhythm analysis using dual digital inclinometry, trunk flexion-extension control testing with kinematic analysis, and dynamic reach stability assessment using force plate technology. The heavy user group subsequently completed a six-week movement re-patterning intervention incorporating segmental spinal control training and dynamic trunk stabilization exercises.

Results: Heavy smartphone users demonstrated significantly reduced lumbar contribution during trunk flexion (38.2% ± 4.6% *vs.* 51.7% ± 5.2%, p<0.001) with compensatory increases in pelvic rotation (26.8° ± 3.4° *vs.* 19.6° ± 2.8°, p<0.001). Dynamic reach stability indices were markedly lower in smartphone users (0.61 ± 0.08 *vs.* 0.82 ± 0.06, p<0.001), indicating compromised trunk control during multidirectional reaching tasks. Post-intervention analysis revealed significant improvements in lumbar contribution (46.3% ± 5.1%, p<0.01) and reach stability (0.74 ± 0.07, p<0.01).

Conclusion: Habitual smartphone use appears to modify dynamic spinal load distribution patterns, characterized by reduced lumbar mobility contribution and altered lumbo-pelvic coordination during functional tasks. These findings suggest that repetitive smartphone postures may induce adaptive changes in motor control strategies that extend beyond static positioning, potentially predisposing individuals to aberrant movement patterns and trunk instability. Movement re-patterning interventions show promise in restoring more optimal spinal loading strategies, though long-term clinical implications warrant further investigation.

Keywords: Smartphone Posture; Lumbo-Pelvic Rhythm; Spinal Biomechanics; Trunk Stabilization; Dynamic Stability; Movement Re-Patterning

Introduction

The ubiquitous integration of smartphones into contemporary society has fundamentally transformed human postural behaviors and movement patterns. Global smartphone penetration exceeded 6.8 billion users in 2023, with average daily usage approaching five hours among young adults

[1]. This technological adoption has coincided with biomechanical consequences that extend beyond simple musculoskeletal discomfort, potentially influencing fundamental motor control strategies and load distribution mechanisms throughout the axial skeleton.

The biomechanical signature of smartphone use is characterized by sustained cervical flexion angles ranging from 45° to 60°, substantially exceeding neutral alignment parameters [2]. This forward head posture generates exponentially increasing gravitational moments on cervical structures, with effective head weight increasing from approximately 4.5 kg in neutral alignment to 12-27 kg at flexion angles commonly observed during smartphone interaction [3]. Concurrent thoracic kyphosis amplification represents a compensatory postural adaptation, yet paradoxically increases vertebral compressive loading throughout thoracolumbar segments [4].

Recent investigations have documented the immediate postural consequences of smartphone interaction during standing and ambulation. Postural photogrammetry studies reveal significant increases in thoracic kyphosis angle and posterior displacement of the upper torso during smartphone engagement, with females demonstrating more pronounced compensatory increases in lumbar lordosis depth [5]. Spinal alignment alterations during smartphone use include increased cervical angle, enhanced kyphosis, and modifications to lordotic curvature, particularly evident during bipedal stance and gait initiation [6]. These findings establish that smartphone interaction acutely modifies sagittal plane spinal curvatures across cervical, thoracic, and lumbar regions.

However, a critical gap exists in understanding how habitual smartphone postures influence dynamic spinal biomechanics during functional movement tasks. Most existing research has focused on static postural deviations or gait parameters during concurrent smartphone use. Substantially less attention has been directed toward investigating whether chronic smartphone exposure induces persistent alterations in neuromuscular control strategies during activities requiring coordinated trunk motion, such as reaching, bending, lifting, or transitional movements. These functional tasks demand precise coordination between lumbar spine motion and pelvic rotation—a relationship termed lumbo-pelvic rhythm—which is fundamental to efficient load transfer and injury prevention [7].

Lumbo-pelvic rhythm represents the temporal and spatial coordination between lumbar spine flexion-extension and pelvic anterior-posterior rotation during sagittal plane trunk movements [8]. In healthy individuals performing forward trunk flexion, the lumbar spine contributes approximately 50-60% of total trunk inclination, with the pelvis providing the remaining contribution through anterior rotation about the femoral heads [9]. This coordinated pattern ensures optimal load distribution across spinal segments, minimizes localized stress concentrations, and maintains muscular efficiency throughout the movement range. Disruptions to lumbo-pelvic rhythm, characterized by either excessive or insufficient lumbar contribution relative to pelvic motion, have been consistently associated with low back disorders and altered trunk muscle recruitment patterns [10].

The mechanistic pathway linking smartphone posture to altered dynamic spinal control likely involves multiple interrelated factors. Sustained cervical flexion and thoracic kyphosis modify proprioceptive input from cervical and thoracic mechanoreceptors, potentially degrading central nervous system representations of spinal position and motion [11]. Chronic positioning in thoracic flexion may promote adaptive shortening of anterior thoracic structures while lengthening posterior musculature, shifting optimal length-tension relationships and altering force generation capabilities [12]. Furthermore, increased thoracic kyphosis substantially elevates compressive loads throughout thoracolumbar segments even during static stance, with biomechanical modeling demonstrating near-linear relationships between kyphosis angle and vertebral loading magnitude [13].

These postural and loading modifications may induce compensatory motor control adaptations. When thoracic extension mobility is restricted due to habitual kyphotic positioning, the central nervous system may develop alternative movement strategies that rely more heavily on pelvic rotation and less on lumbar spine motion during trunk flexion tasks [14]. Such adaptations, while potentially effective for task completion in the short term, may constitute suboptimal loading patterns that increase segmental stress, reduce movement efficiency, and potentially predispose individuals to musculoskeletal injury during repetitive or high-load activities.

Recent advances in wearable sensor technology have enhanced capabilities for quantifying lumbo-pelvic rhythm in both laboratory and functional environments [15]. Dual inclinometer systems and inertial measurement units enable precise characterization of segmental contributions to trunk motion, facilitating identification of subtle coordination abnormalities that may not be apparent through observational analysis. Similarly, force platform assessment during dynamic reaching tasks provides sensitive measures of postural stability and motor control quality during functionally relevant movements requiring integration of visual, vestibular, and proprioceptive information [16].

Despite these methodological advances and growing recognition of smartphone-related postural changes, no previous investigations have systematically examined whether habitual smartphone use influences lumbo-pelvic rhythm and dynamic trunk control during functional tasks performed in the absence of smartphone distraction. Understanding these relationships is clinically relevant, as altered movement patterns may persist beyond immediate smartphone interaction periods, potentially reflecting central nervous system adaptations rather than simple biomechanical constraints imposed by device handling.

Furthermore, if smartphone-associated postural habits do influence dynamic spinal control, determining whether targeted interventions can restore more optimal movement patterns becomes paramount. Movement re-patterning approaches, which emphasize conscious modification of habitual motor strategies through feedback and practice, have demonstrated efficacy in various musculoskeletal populations [17]. Trunk stabilization exercises, designed to enhance neuromuscular control of spinal segments and improve coordination between local and global muscle systems, represent another evidence-based intervention strategy [18]. The potential synergistic effects of combining these approaches for individuals demonstrating smartphone-related movement alterations warrants investigation.

Central Hypothesis

This study was designed to test the central hypothesis that habitual smartphone use modifies dynamic spinal load distribution patterns during functional movement tasks, specifically manifesting as altered lumbo-pelvic rhythm characterized by reduced lumbar contribution and compensatory pelvic motion dominance. We further hypothesized that smartphone users would demonstrate compromised trunk stability during dynamic reaching tasks, and that a structured movement re-patterning intervention incorporating trunk stabilization training would improve dynamic spinal control parameters toward more optimal patterns.

Objectives

Primary Objective

To determine whether habitual smartphone use is associated with alterations in spinal segmental load distribution and lumbo-pelvic rhythm during dynamic trunk flexion tasks performed in the absence of smartphone distraction.

Secondary Objectives

1. To evaluate trunk flexion-extension control quality during standardized functional movement tasks, comparing smartphone users with matched controls.
2. To assess dynamic postural stability during multidirectional reaching tasks using center of pressure displacement and trunk sway parameters.
3. To determine the effectiveness of a six-week movement re-patterning and trunk stabilization intervention on restoring optimal dynamic spinal control in habitual smartphone users.
4. To explore relationships between daily smartphone usage duration and magnitude of biomechanical alterations in lumbo-pelvic coordination.

Hypotheses

H1: Frequent smartphone users will demonstrate altered lumbo-pelvic rhythm during trunk flexion tasks, characterized by significantly reduced lumbar spine contribution (<45%) and compensatory increases in pelvic rotation compared to low smartphone users.

H2: Smartphone users will exhibit reduced dynamic trunk stability during multidirectional reaching tasks, evidenced by increased center of pressure displacement and lower reach stability indices compared to controls.

H3: A structured movement re-patterning intervention incorporating segmental spinal control training and dynamic trunk stabilization exercises will produce significant improvements in lumbo-pelvic rhythm parameters and dynamic stability measures in smartphone users.

H4: The magnitude of lumbo-pelvic rhythm disruption will demonstrate positive correlation with daily smartphone usage duration, suggesting a dose-response relationship between exposure and biomechanical consequences.

Methodology

Study Design

This investigation employed a controlled quasi-experimental design with between-group comparisons and within-group pre-post intervention analysis. The study received ethical approval from the Institutional Review Board (Protocol Number: IRB-2024-0847), and all procedures were conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants following comprehensive explanation of study procedures, potential risks, and participant rights.

Participants

Sample Size Determination: Sample size calculation was performed using G*Power 3.1 software based on preliminary data from pilot testing. Assuming a moderate effect size (d = 0.65) for the primary outcome variable (lumbar contribution percentage during trunk flexion), alpha level of 0.05, and desired power of 0.80, a minimum of 23 participants per group was required. Accounting for potential 15% attrition, target recruitment was set at 27 participants per group (N = 54 total).

Recruitment and Group Allocation: Fifty-four healthy adults aged 18-30 years were recruited from university campuses and community centers through posted advertisements and digital announcements. Participants were allocated into two groups based on self-reported smartphone usage patterns verified through smartphone application usage tracking data:

- **Group A (Heavy Smartphone Users):** Daily smartphone use exceeding 4 hours (n=27; 14 males, 13 females; mean age 23.2 ± 2.6 years)
- **Group B (Low Smartphone Users):** Daily smartphone uses less than 1 hour (n=27; 13 males, 14 females; mean age 22.7 ± 2.8 years)

Smartphone usage was quantified using built-in screen time monitoring features on participants' devices, with verification over a two-week period prior to baseline assessment.

Inclusion Criteria:

1. Age between 18 and 30 years.
2. Consistent smartphone usage pattern for minimum 12 months meeting group criteria.
3. Ability to perform trunk flexion to at least 90 degrees.
4. Willingness to complete all assessment and intervention sessions.
5. Absence of current musculoskeletal pain limiting movement (Visual Analog Scale <3/10).

Exclusion Criteria:

1. History of spinal surgery or instrumentation.
2. Diagnosed neurological disorders affecting motor control (e.g., multiple sclerosis, Parkinson's disease, stroke).
3. Structural spinal deformities (scoliosis >10° Cobb angle, spondylolisthesis).
4. Acute low back pain within previous three months requiring medical intervention.
5. Vestibular disorders affecting balance.
6. Pregnancy or within six months postpartum.
7. Body mass index exceeding 32 kg/m^2 (to minimize biomechanical confounding).
8. Current participation in structured trunk stabilization or core training programs.

Assessment Procedures

All biomechanical assessments were conducted in a controlled laboratory environment by the same experienced assessor (10+ years clinical experience in musculoskeletal assessment) who was blinded to group allocation. Participants wore standardized athletic clothing and were barefoot for all testing. A 10-minute familiarization period preceded formal testing to ensure task comprehension and minimize learning effects.

Lumbo-Pelvic Rhythm Analysis: Lumbo-pelvic rhythm was quantified using dual digital inclinometry (Baseline Digital Inclinometer, Fabrication Enterprises Inc., accuracy ±0.5°) with established reliability

(ICC = 0.89-0.94) [19]. Anatomical landmarks were identified through palpation and marked with adhesive markers: spinous process of T12 (thoracolumbar junction), spinous process of S2 (sacral base), and the midpoint between posterior superior iliac spines.

Testing Protocol:

1. Participants assumed relaxed standing position with feet hip-width apart.
2. One inclinometer was positioned at T12 (measuring lumbar spine angle), and a second at S2 (measuring pelvic tilt angle).
3. Participants performed slow, controlled trunk flexion (reaching toward toes while keeping knees extended) at a standardized cadence (metronome-paced at 60 beats/minute for 4-second descent, 4-second return).
4. Inclinometer readings were recorded at: neutral standing, 45° trunk flexion, maximal trunk flexion, and return to neutral.
5. Three trials were performed with 60-second rest intervals; mean values were used for analysis.

Outcome Variables:

- **Lumbar flexion contribution (%):** (Lumbar angle change / Total trunk flexion angle) × 100.
- **Pelvic rotation angle (degrees):** Absolute change in sacral base angle from neutral to maximal flexion.
- **Lumbo-pelvic ratio:** Ratio of lumbar flexion to pelvic rotation at maximum trunk flexion.
- **Temporal coordination:** Timing differential between initiation of lumbar motion and pelvic rotation (derived from video analysis).

Trunk Flexion-Extension Control Test: Dynamic trunk control was assessed using three-dimensional motion capture (Vicon Motion Systems, 8-camera setup, 100 Hz sampling) with reflective markers positioned at C7, T6, T12, L3, S1, bilateral iliac crests, and greater trochanters according to a modified Helen Hayes marker set.

Testing Protocol:

1. Participants stood on a designated platform within the calibrated capture volume.
2. Tasks performed:
   - **Controlled flexion-extension cycles:** Five repetitions of trunk flexion to 60° and return at self-selected comfortable speed.
   - **Variable speed flexion:** Flexion performed at three speeds (slow: 6 seconds, moderate: 3 seconds, fast: 1.5 seconds) to assess motor control adaptability.
3. Verbal encouragement emphasized movement smoothness and control rather than speed or range.

Outcome Variables:

- **Angular velocity (degrees/second):** Peak flexion and extension velocities.
- **Movement smoothness index:** Calculated using spectral arc length method from angular velocity profiles[20].
- **Trunk control variability:** Standard deviation of segmental angular velocities across repetitions.
- **Segmental coordination:** Phase lag between thoracic and lumbar motion initiation.

Dynamic Reach Stability Test: Postural stability during reaching was quantified using a force platform (AMTI OR6-7, 1000 Hz sampling) synchronized with motion capture to assess center of pressure (COP) displacement during multidirectional reaching tasks.

Testing Protocol:

1. Participants stood barefoot in standardized position (feet hip-width, arms at sides) on force platform.
2. Visual targets were positioned at 80% of maximum reach distance in eight directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° relative to forward direction).
3. On auditory cue, participants reached with dominant arm to touch target, held for 2 seconds, then returned to starting position.
4. Three trials per direction were performed in randomized order with 30-second inter-trial intervals.
5. Participants were instructed to maintain single-leg stance base (no stepping allowed) and minimize trunk lean.

Outcome Variables:

- **Reach stability index:** Composite score derived from COP displacement normalized to reach distance (values approaching 1.0 indicate better stability) [21].
- **COP displacement (cm):** Total excursion in anteroposterior and mediolateral directions.
- **Trunk sway amplitude (degrees):** Maximum angular deviation from vertical measured at T12 marker.
- **Reach distance (cm):** Distance achieved relative to maximum reach capacity (percentage).

Intervention Protocol

Following baseline assessment, Group A (heavy smartphone users) participated in a six-week supervised movement re-patterning and trunk stabilization program. Group B (low users) continued normal activities without intervention, serving as a natural control group. The intervention was designed based on current evidence for motor learning and trunk stabilization principles [22, 23].

Program Structure:

- **Duration:** Six weeks.
- **Frequency:** Three supervised sessions per week (18 total

sessions).

- **Session length:** 45 minutes (including warm-up and cool-down).
- **Supervision:** Licensed physiotherapist with specialization in movement analysis.
- **Location:** University biomechanics laboratory with appropriate equipment.

Intervention Components:

Phase 1 (Weeks 1-2): Foundation and Awareness

Segmental Spinal Control Training:

- Isolated lumbar flexion and extension in quadruped position (4 sets × 10 repetitions).
- Pelvic tilting exercises with tactile feedback for dissociation from lumbar motion.
- Thoracic extension mobilization exercises (cat-camel variations).
- Mirror feedback exercises for postural awareness during simulated smartphone positioning.

Basic Trunk Stabilization:

- Abdominal bracing techniques (transversus abdominis activation).
- Static prone plank (progressing from 15-second holds to 45-second holds).
- Side plank modifications (knees bent progressing to extended).
- Supine dead bug exercises (contralateral limb movements with neutral spine maintenance).

Phase 2 (Weeks 3-4): Integration and Dynamic Control

Lumbo-Pelvic Coordination Training:

- Standing trunk flexion with visual feedback (mirror or video) emphasizing increased lumbar contribution.
- Hip hinge movement pattern training with dowel contact along spine.
- Segmental flexion-extension sequences (curl-down and roll-up exercises).
- Seated reaching tasks with pelvic stabilization cues.

Progressive Trunk Stabilization:

- Unstable surface plank variations (BOSU, stability ball).
- Dynamic planks (shoulder taps, limb elevations).
- Pallof press variations (anti-rotation exercises).
- Quadruped bird-dog exercises with tempo variations.

Phase 3 (Weeks 5-6): Functional Movement Retraining

Task-Specific Integration:

- Functional reaching patterns with stability requirements.
- Lifting mechanics training emphasizing optimal lumbo-pelvic coordination.
- Transitional movements (sit-to-stand, squat variations).
- Dual-task conditions (reaching while maintaining balance challenges).

Advanced Stabilization:

- Single-leg stance variations with perturbations.
- Swiss ball rollouts and stir-the-pot exercises.
- Standing cable resisted rotational movements.
- Movement pattern corrections with real-time biofeedback.

Progression Principles:

Exercise difficulty was progressed based on individual performance using these criteria:

1. Ability to maintain neutral spinal alignment throughout movement.
2. Demonstration of smooth, controlled motion without compensatory strategies.
3. Completion of target repetitions/hold durations without fatigue-related form breakdown.
4. Participant confidence rating ≥7/10 for exercise execution.

Participants were provided with home exercise programs (15 minutes daily) emphasizing postural awareness and basic stabilization exercises to complement supervised sessions.

Post-Intervention Assessment

All baseline assessment procedures were repeated at the conclusion of the six-week intervention period for Group A participants. Group B was reassessed at equivalent time intervals to control for potential practice effects or temporal variations. The same assessor, maintained blinding to intervention status, conducted all post-intervention testing using identical protocols and equipment.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics Version 28.0 with significance level set at $\alpha = 0.05$. Data distribution normality was assessed using Shapiro-Wilk tests and visual inspection of Q-Q plots. Descriptive statistics (mean ± standard deviation) were calculated for all variables.

Between-Group Comparisons (Baseline): Independent samples t-tests compared baseline outcome measures between heavy smartphone users and low users. Levene's test verified homogeneity of variance assumptions.

Within-Group Changes (Intervention Effects): Paired samples t-tests evaluated pre-intervention to post-intervention changes within Group A. Effect sizes were calculated using Cohen's d (small: 0.2-0.5, moderate: 0.5-0.8, large: >0.8).

Mixed-Design Analysis: Two-way mixed ANOVA (2 groups × 2 time points) examined group-by-time interactions for outcome variables, with Greenhouse-Geisser corrections applied when sphericity assumptions were violated.

Correlation Analysis: Pearson correlation coefficients examined relationships between smartphone usage duration and biomechanical outcome variables.

Additional Analyses: Chi-square tests compared categorical demographic variables between groups. Analysis of covariance (ANCOVA) explored influence of potential confounding variables (age, BMI, physical activity level) on primary outcomes.

Results

Participant Characteristics

All 54 recruited participants completed baseline assessments. In Group A, two participants withdrew during the intervention period (one due to scheduling conflicts, one due to unrelated injury), resulting in 25 participants completing the full protocol. Group B maintained complete participation (n=27). No adverse events related to study procedures were reported.

Demographic and anthropometric characteristics are presented in Table 1. Groups demonstrated equivalence for age, sex distribution, body mass index, and general physical activity levels, confirming successful matching on relevant confounding variables. As expected by design, daily smartphone usage duration differed substantially between groups (p<0.001).

Baseline Between-Group Comparisons

Lumbo-Pelvic Rhythm Parameters: Heavy smartphone users demonstrated significantly altered lumbo-pelvic rhythm patterns compared to low users (Table 2). The most striking finding was reduced lumbar contribution to trunk flexion in smartphone users (38.2% ± 4.6%) compared to controls (51.7% ± 5.2%), representing a 26% relative reduction (t(50) = 9.82, p<0.001, d = 2.76). This was accompanied by compensatory increases in pelvic rotation angle among smartphone users (26.8° ± 3.4° *vs*. 19.6° ± 2.8°; t(50) = 8.14, p<0.001, d = 2.35).

The lumbo-pelvic ratio, reflecting the relative contribution of lumbar flexion to pelvic rotation, was significantly lower in smartphone users (0.58 ± 0.12 *vs*. 1.03 ± 0.18; p<0.001), indicating a fundamental shift toward pelvic-dominant movement strategies. Temporal coordination analysis revealed that smartphone users initiated pelvic rotation significantly earlier relative to lumbar motion onset (142 ± 38 ms earlier) compared to controls, suggesting altered motor planning or reduced anticipatory lumbar muscle activation.

Trunk Flexion-Extension Control: Smartphone users demonstrated compromised trunk control quality across multiple parameters. Movement smoothness index, which quantifies the continuity and coordination of motion (values approaching 1.0 indicate smoother movement), was significantly reduced in smartphone users (0.68 ± 0.09 *vs*. 0.82 ± 0.08; p<0.001). This suggests more fragmented, less coordinated movement execution potentially reflecting disrupted motor planning or reduced proprioceptive feedback integration.

Table 1: Demographic and anthropometric characteristics of study participants (Mean ± SD).

Variable	Smartphone Users (n=25)	Controls (n=27)	p-value
Age (years)	23.2 ± 2.6	22.7 ± 2.8	0.52
Sex (M/F)	13/12	13/14	0.79[a]
Height (cm)	168.4 ± 8.9	169.7 ± 9.2	0.61
Mass (kg)	65.8 ± 11.2	66.9 ± 10.8	0.71
BMI (kg/m^2)	23.1 ± 2.7	23.2 ± 2.5	0.89
Daily smartphone use (hours)	5.2 ± 1.1	0.8 ± 0.3	<0.001
Physical activity (IPAQ score)	2847 ± 986	2923 ± 1042	0.78
Years of smartphone ownership	8.6 ± 1.9	8.2 ± 2.1	0.48

Note: BMI = Body Mass Index; IPAQ = International Physical Activity Questionnaire; [a]Chi-square test; All other comparisons used independent t-tests.

Control variability, assessed through standard deviation of segmental angular velocities across repeated trials, was 50% higher in smartphone users (4.2 ± 1.1 *vs*. 2.8 ± 0.9; p<0.001), indicating reduced movement consistency and motor control precision. Segmental coordination analysis revealed significant delays in thoracic-lumbar motion sequencing among smartphone users, with thoracic motion preceding lumbar flexion by 186 ± 47 ms compared to 124 ± 38 ms in controls (p<0.001).

Dynamic Reach Stability: Dynamic postural stability during reaching tasks was markedly compromised in heavy smartphone users (Table 2). The reach stability index, a composite measure of postural control during reaching, was 25% lower in smartphone users (0.61 ± 0.08 *vs*. 0.82 ± 0.06; p<0.001, d = 2.93), indicating substantial deficits in maintaining equilibrium during limb displacement tasks.

Center of pressure displacement increased by 47% in smartphone users (8.7 ± 1.6 cm *vs*. 5.9 ± 1.2 cm; p<0.001), reflecting greater postural adjustments required to maintain balance during reaching. Trunk sway amplitude was similarly elevated (12.4° ± 2.3° *vs*. 8.1° ± 1.8°; p<0.001), suggesting reduced trunk stiffness or inadequate anticipatory postural adjustments.

Interestingly, smartphone users also achieved lower reach distances as a percentage of their maximum capacity (82.6% ± 7.4% *vs*. 91.3% ± 6.2%; p<0.001), potentially reflecting conservative motor strategies adopted in response to perceived instability or reduced confidence in postural control capabilities (Figure 1).

Dose-Response Relationship

Correlation analysis examined relationships between daily smartphone usage hours and biomechanical outcome variables across all participants. Significant moderate-to-strong negative correlations emerged between usage duration and lumbar contribution percentage (r = -0.72, p<0.001), reach stability index (r = -0.68, p<0.001), and movement smoothness (r = -0.61, p<0.001). Conversely, positive correlations were observed between usage duration and pelvic rotation angle (r = 0.66, p<0.001) and COP displacement (r = 0.59,

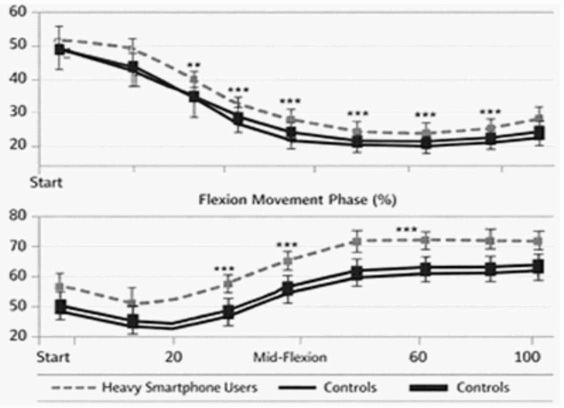

Figure 1: Lumbar versus pelvic contribution during trunk flexion movement phases. Heavy smartphone users (dashed line) demonstrate reduced lumbar contribution and compensatory increases in pelvic rotation throughout the flexion cycle compared to controls (solid line). Error bars represent standard error of the mean.

Table 2: Baseline biomechanical outcome measures (Mean ± SD).

Variable	Smartphone Users	Controls	p-value	Effect Size (d)
Lumbo-Pelvic Rhythm				
Lumbar contribution (%)	38.2 ± 4.6	51.7 ± 5.2	<0.001	2.76
Pelvic rotation angle (°)	26.8 ± 3.4	19.6 ± 2.8	<0.001	2.35
Lumbo-pelvic ratio	0.58 ± 0.12	1.03 ± 0.18	<0.001	2.98
Temporal coordination (ms)	142 ± 38	52 ± 28	<0.001	2.67
Trunk Control Parameters				
Peak flexion velocity (°/s)	47.3 ± 8.2	52.6 ± 7.8	0.02	0.66
Movement smoothness index	0.68 ± 0.09	0.82 ± 0.08	<0.001	1.64
Control variability (SD)	4.2 ± 1.1	2.8 ± 0.9	<0.001	1.38
Segmental coordination (ms)	186 ± 47	124 ± 38	<0.001	1.45
Dynamic Stability				
Reach stability index	0.61 ± 0.08	0.82 ± 0.06	<0.001	2.93
COP displacement (cm)	8.7 ± 1.6	5.9 ± 1.2	<0.001	1.98
Trunk sway amplitude (°)	12.4 ± 2.3	8.1 ± 1.8	<0.001	2.08
Reach distance (% max)	82.6 ± 7.4	91.3 ± 6.2	<0.001	1.27

Note: All comparisons significant at p<0.05; Effect size interpretation: small (0.2-0.5), moderate (0.5-0.8), large (>0.8).

Table 3: Pre-intervention and post-intervention outcome measures in Group A (Smartphone Users, n=25).

Variable	Pre-intervention	Post-intervention	p-value	Effect Size (d)
Lumbo-Pelvic Rhythm				
Lumbar contribution (%)	38.2 ± 4.6	46.3 ± 5.1	<0.001	1.64
Pelvic rotation angle (°)	26.8 ± 3.4	23.1 ± 3.2	<0.001	1.11
Lumbo-pelvic ratio	0.58 ± 0.12	0.79 ± 0.14	<0.001	1.62
Trunk Control				
Movement smoothness index	0.68 ± 0.09	0.77 ± 0.08	<0.001	1.05
Control variability (SD)	4.2 ± 1.1	3.2 ± 0.9	<0.001	0.99
Dynamic Stability				
Reach stability index	0.61 ± 0.08	0.74 ± 0.07	<0.001	1.70
COP displacement (cm)	8.7 ± 1.6	7.1 ± 1.4	<0.001	1.06
Trunk sway amplitude (°)	12.4 ± 2.3	9.8 ± 2.0	<0.001	1.21

p<0.001). These findings suggest a dose-response relationship wherein greater smartphone exposure associates with more pronounced biomechanical alterations.

Intervention Effects

Within-Group Changes (Group A): The six-week movement re-patterning and trunk stabilization intervention produced significant improvements across multiple outcome measures in Group A participants (Table 3). Lumbar contribution percentage increased from 38.2% ± 4.6% at baseline to 46.3% ± 5.1% post-intervention, representing a 21% relative improvement (t(24) = 6.83, p<0.001, d = 1.64). While this remained below control group values, the magnitude of change was clinically meaningful and statistically significant.

Pelvic rotation angle decreased from 26.8° ± 3.4° to 23.1° ± 3.2° (t(24) = 4.51, p<0.001, d = 1.11), indicating partial normalization of pelvic contribution toward more balanced lumbo-pelvic coordination. The lumbo-pelvic ratio improved significantly from 0.58 ± 0.12 to 0.79 ± 0.14 (p<0.001), reflecting enhanced proportional relationship between lumbar and pelvic motion.

Trunk control quality also improved substantially. Movement smoothness index increased from 0.68 ± 0.09 to 0.77 ± 0.08 (p<0.001, d = 1.05), and control variability decreased from 4.2 ± 1.1 to 3.2 ± 0.9 (p<0.001, d = 0.99), demonstrating enhanced motor control consistency and coordination.

Dynamic reach stability showed marked improvement, with the reach stability index increasing 21% from 0.61 ± 0.08 to 0.74 ± 0.07 (p<0.001, d = 1.70). Center of pressure displacement decreased by 18% (8.7 ± 1.6 cm to 7.1 ± 1.4 cm; p<0.001), and trunk sway amplitude reduced by 21% (12.4° ± 2.3° to 9.8° ± 2.0°; p<0.001), collectively indicating substantially improved postural control during dynamic tasks (Figure 2).

Mixed-Design ANOVA Results: Two-way mixed ANOVA (2 groups × 2 time points) revealed significant group-by-time interactions for primary outcome variables including lumbar contribution (F(1,50) = 28.47, p<0.001, partial $\eta^2 = 0.36$), lumbo-pelvic ratio (F(1,50) = 24.82, p<0.001, partial $\eta^2 = 0.33$), and reach stability index (F(1,50) = 31.56, p<0.001, partial $\eta^2 = 0.39$). These interactions confirm that changes over time differed significantly between groups, attributable to intervention effects rather than temporal variation or practice effects.

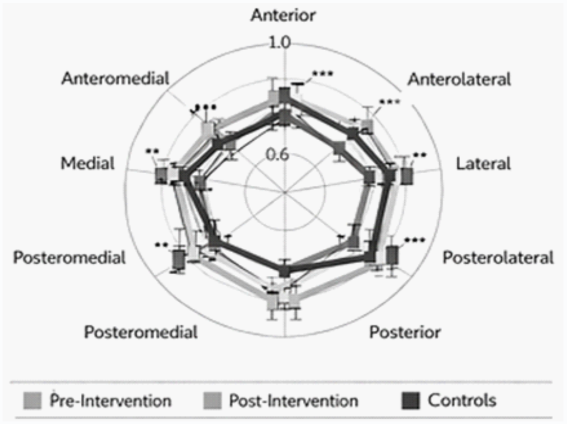

Figure 2: Dynamic reach stability indices across eight reach directions. Smartphone users pre-intervention (light gray) demonstrates reduced stability across all reach directions compared to controls (dark gray). Post-intervention values (medium gray) show significant improvements toward control levels. Error bars represent 95% confidence intervals. Asterisks indicate significant differences (* p<0.05, ** p<0.01, *** p<0.001).

Control Group Stability (Group B): Reassessment of Group B participants at equivalent time intervals revealed no significant changes in any outcome measure (all p>0.30), with mean differences less than measurement error thresholds. This confirms test-retest stability and rules out practice effects as explanations for Group A improvements.

Discussion

This investigation provides novel evidence that habitual smartphone use is associated with substantial alterations in dynamic spinal load distribution patterns during functional movement tasks. Specifically, heavy smartphone users demonstrated significantly reduced lumbar contribution to trunk flexion with compensatory pelvic motion dominance, compromised trunk control quality, and degraded postural stability during dynamic reaching. These findings extend previous research documenting static postural deviations during smartphone interaction by revealing that biomechanical consequences persist during functional activities performed in the absence of device handling, suggesting central nervous system adaptations rather than simple mechanical constraints.

Altered Lumbo-Pelvic Rhythm: Mechanisms and Implications

The 26% reduction in lumbar contribution observed among smartphone users represents a clinically and biomechanically significant deviation from established norms. Previous investigations of lumbo-pelvic rhythm in healthy populations consistently report lumbar contributions of 50-60% during trunk flexion [9, 15], with our control group results (51.7%) aligning with this normative range. The smartphone users' pattern (38.2% lumbar, elevated pelvic rotation) more closely resembles patterns documented in individuals with chronic low back pain or movement impairments [10].

Several interconnected mechanisms likely contribute to this altered coordination pattern. First, habitual thoracic kyphosis associated with smartphone posture may restrict thoracic extension mobility through adaptive soft tissue changes. Biomechanical modeling studies demonstrate that increased thoracic kyphosis substantially elevates vertebral compressive loads throughout thoracolumbar segments [13], potentially promoting protective motor strategies that limit lumbar motion to minimize perceived tissue stress. The central nervous system may preferentially adopt pelvic-dominant strategies to accomplish trunk flexion tasks while minimizing loading on potentially sensitized lumbar structures.

Second, sustained forward head and thoracic flexion postures during smartphone use modify proprioceptive input from cervical and thoracic mechanoreceptors. Proprioceptive feedback from spinal structures plays critical roles in motor control, contributing to body schema representations, movement planning, and real-time movement adjustments [11]. Chronic positioning in non-neutral alignments may degrade the accuracy or central interpretation of proprioceptive signals, potentially disrupting the precision of motor commands for segmental spinal control.

Third, repeated positioning in thoracic flexion may induce length-tension relationship adaptations in trunk musculature. Anterior thoracic structures (pectoralis minor, intercostals) may undergo adaptive shortening while posterior extensors (thoracic erector spinae, trapezius) lengthen beyond optimal force-generating positions [12]. These biomechanical changes alter available force production capabilities, potentially constraining movement options and necessitating compensatory strategies involving alternative muscle groups or movement segments.

The temporal coordination findings—smartphone users initiating pelvic rotation 90 ms earlier relative to lumbar motion compared to controls—provide additional insight into the nature of these alterations. This suggests changes in motor planning or feedforward control strategies rather than simple biomechanical restrictions. Anticipatory postural adjustments and movement sequencing reflect central nervous system motor programs developed through repetition and experience. The altered temporal patterns observed in smartphone users may represent consolidated motor programs adapted to habitual postural constraints, persisting even when those constraints are temporarily absent during testing.

Compromised Dynamic Trunk Control

The reduced movement smoothness and increased variability observed among smartphone users indicate degraded motor control quality beyond simple coordination pattern differences. Movement smoothness, quantified through spectral arc length analysis, reflects the efficiency and coordination of neuromuscular control [20]. Reduced smoothness suggests more fragmented motor commands, potentially indicating disrupted sensorimotor integration, reduced motor planning efficiency, or inadequate muscle synergy organization.

The 50% increase in control variability among smartphone users is particularly noteworthy. Increased movement variability often reflects reduced motor control precision or instability in motor programs. While some movement variability is normal and potentially beneficial for motor learning, excessive variability typically indicates suboptimal motor control and may increase injury risk through exposure to extreme loading scenarios during the variable movement attempts [24].

Segmental coordination delays between thoracic and lumbar motion further support the interpretation that smartphone-related alterations extend to fundamental motor control organization. Coordinated multi-segment movements require precise temporal sequencing to achieve smooth, efficient motion. The 50% increase in thoracic-lumbar phase lag among smartphone users suggests disrupted intersegmental coordination, potentially reflecting altered muscle activation patterns, proprioceptive feedback disruptions, or central motor programming changes.

Dynamic Reach Stability Deficits

The substantial deficits in dynamic reach stability (25% reduction in stability index) among smartphone users represent functionally significant impairments with potential implications for fall risk and task performance. Dynamic reaching tasks require integration of visual, vestibular, and proprioceptive information to generate appropriate anticipatory postural adjustments and reactive balance responses. The observed deficits suggest that habitual smartphone posture may influence not only spinal movement patterns but broader sensorimotor integration capabilities.

Several mechanisms may contribute to reduced reach stability. Forward head posture alters cervical proprioceptive input and may affect vestibular system function through changes in head-on-trunk positioning [25]. Increased thoracic kyphosis shifts the body's center of mass anteriorly, altering the biomechanical demands for maintaining equilibrium and potentially requiring greater muscular effort for postural control. Additionally, the altered trunk muscle recruitment patterns associated with habitual flexed positioning may reduce the capacity for generating rapid, coordinated trunk muscle responses necessary for effective balance control during perturbations.

The correlation between smartphone usage duration and reach stability deficits (r = -0.68) suggests a dose-response relationship, strengthening the argument for causal linkage rather than spurious association. This finding has practical implications for risk stratification and prevention, suggesting that individuals with highest usage volumes may warrant particular attention for assessment and intervention.

Intervention Effectiveness and Clinical Implications

The significant improvements observed following the six-week movement re-patterning and trunk stabilization intervention provide encouraging evidence for the modifiability of smartphone-associated biomechanical alterations. The 21% increase in lumbar contribution and 21% improvement in reach stability index represent clinically meaningful changes, though full normalization was not achieved within this timeframe.

The intervention's theoretical foundation combined motor learning principles (conscious movement pattern modification, feedback, repetition) with neuromuscular training approaches (trunk stabilization, segmental control). The effectiveness of this combined approach aligns with emerging evidence that optimal motor control requires both adequate muscular capacity (strength, endurance, coordination) and appropriate motor programming (movement patterns, muscle recruitment strategies) [22, 23].

Several intervention components likely contributed synergistically to observed improvements. Segmental spinal control exercises specifically addressed the reduced lumbar mobility contribution by training isolated lumbar flexion-extension control with reduced pelvic involvement. Mirror and video feedback provided external reference information to facilitate conscious modification of habitual movement patterns. Progressive trunk stabilization exercises enhanced neuromuscular control capacity, potentially providing a foundation for implementing modified movement strategies during functional tasks.

The persistent gap between post-intervention smartphone user values and control group values suggests that complete reversal of adaptations may require longer intervention durations, higher training volumes, or additional intervention components. Alternatively, some adaptations may represent relatively stable central nervous system reorganization resistant to short-term retraining. Longitudinal investigations examining intervention effects over extended timeframes (3-6 months) would clarify whether continued improvements occur with sustained training or whether plateaus are encountered.

From a clinical perspective, these findings suggest that physiotherapists and movement specialists should consider screening heavy smartphone users for movement pattern alterations even in the absence of pain or functional complaints. Early identification and intervention may prevent progression to symptomatic conditions. Assessment should include evaluation of lumbo-pelvic rhythm, trunk control quality during functional movements, and dynamic balance capabilities.

Intervention approaches should emphasize movement re-education rather than focusing exclusively on strengthening or stretching. While addressing tissue-level restrictions (e.g., thoracic extension mobility limitations) remains important, consciously modifying habitual motor strategies through feedback, practice, and functional task training appears critical for addressing centrally-mediated adaptations. Integration of postural awareness education, particularly regarding smartphone usage habits, may enhance intervention effectiveness by addressing causal behaviors alongside compensatory movement patterns.

Broader Implications for Musculoskeletal Health

These findings have implications beyond immediate biomechanical alterations. Suboptimal movement patterns, particularly those involving altered load distribution across spinal segments, represent recognized risk factors for development of musculoskeletal disorders [26]. Chronic exposure to elevated segmental loading, as would result from pelvic-dominant flexion patterns requiring greater muscular force for equivalent trunk displacement, may accelerate degenerative processes in spinal motion segments.

Additionally, reduced dynamic stability and trunk control represent functional limitations that may impact athletic performance, occupational task execution, and activities of daily living. Fall risk, while primarily studied in elderly populations, relates fundamentally to dynamic balance capabilities that appear compromised in young adult smartphone users based on current findings.

The dose-response relationships observed between smartphone usage duration and biomechanical alterations suggest that reducing exposure may represent a viable primary prevention strategy. Public health initiatives promoting awareness of postural consequences and encouraging regular postural variation during smartphone use may have population-level benefits. Ergonomic recommendations, such as bringing devices to eye level rather than flexing the spine toward devices, warrant emphasis in health promotion efforts.

Limitations

Several limitations warrant consideration when interpreting these findings. First, the quasi-experimental design with non-randomized group allocation introduces potential selection bias. While groups were well-matched on measured demographic variables, unmeasured confounders (e.g., genetic predispositions, early developmental factors, personality traits correlating with technology adoption) could potentially contribute to observed differences. Future investigations employing randomized controlled designs would strengthen causal inference, though ethical and practical constraints limit feasibility of randomly assigning smartphone usage patterns.

Second, smartphone usage was primarily quantified through duration rather than postural quality during use. Variations in how individuals position themselves during smartphone interaction (e.g., degree of cervical flexion, presence of upper limb support, sitting versus standing) likely influence biomechanical consequences. More detailed characterization of usage patterns through postural monitoring would enhance understanding of dose-response relationships.

Third, the six-week intervention duration, while sufficient to demonstrate significant improvements, may not represent optimal training duration for maximizing outcomes. Longer-term follow-up was not conducted, leaving questions about sustainability of improvements and potential for continued progress with extended training.

Fourth, the young adult sample limits generalizability to other age groups. Biomechanical consequences of smartphone use may differ in adolescents (whose musculoskeletal systems remain developing) or older adults (who may have existing degenerative changes or reduced adaptive capacity). Investigations across broader age ranges would clarify age-specific vulnerabilities and intervention needs.

Fifth, while objective motion analysis provided precise quantification of movement patterns, these laboratory-based assessments may not fully represent movement strategies employed during unconstrained functional activities in natural environments. Wearable sensor technology enabling assessment during daily activities could provide complementary ecological validity.

Future Research Directions

Several important questions remain for future investigation. Longitudinal studies tracking individuals over months to years would clarify whether observed cross-sectional differences truly reflect smartphone-induced changes versus pre-existing differences that might influence smartphone adoption patterns. Prospective cohort designs could establish temporal relationships and potentially identify critical exposure thresholds beyond which biomechanical alterations emerge.

Interventional studies with longer follow-up periods (6-12 months) would determine whether improvements continue, plateau, or require ongoing training for maintenance. Investigation of different intervention components in factorial designs could identify most effective elements, optimizing resource allocation and treatment efficiency.

Examination of clinical outcomes, including pain incidence, functional limitations, and quality of life measures, would establish whether biomechanical alterations documented here translate to clinically meaningful consequences. This would strengthen rationale for widespread screening and intervention implementation.

Neurophysiological investigations employing electromyography, transcranial magnetic stimulation, or functional neuroimaging could elucidate central nervous system mechanisms underlying observed motor control alterations. Understanding whether changes primarily reflect cortical motor planning alterations, spinal reflex modulation, or muscle synergy reorganization would inform intervention design.

Finally, investigations of preventive strategies, including ergonomic modifications to smartphone use, postural variation protocols during extended use, and prophylactic exercise programs, could establish evidence-based prevention guidelines for public health implementation.

Clinical Implications

Based on current findings, several clinical implications emerge for physiotherapy and rehabilitation practice:

1. **Assessment Considerations:** Physiotherapists should consider evaluating lumbo-pelvic rhythm and dynamic trunk control in patients with heavy smartphone usage, particularly when assessing individuals presenting with spinal pain or movement dysfunction. Altered movement patterns may exist even in asymptomatic individuals, representing potential targets for preventive intervention.

2. **Intervention Strategies:** Treatment approaches for smartphone-associated movement alterations should emphasize movement re-patterning and motor control training rather than focusing exclusively on traditional strength or flexibility interventions. Integration of conscious movement modification with feedback, segmental control training, and progressive trunk stabilization appears most appropriate based on current evidence.

3. **Patient Education:** Health professionals should educate patients about postural consequences of prolonged smartphone use, encouraging regular postural variation, periodic breaks, and ergonomic positioning strategies (bringing device to eye level rather than flexing spine toward device).

4. **Prevention Programs:** Institutions with populations at high risk for sustained smartphone use (universities, technology companies) may benefit from implementing preventive movement programs targeting trunk control, spinal mobility, and postural awareness to mitigate potential biomechanical consequences.

5. **Interdisciplinary Collaboration:** Given the multifaceted nature of smartphone-related musculoskeletal impacts, collaboration between physiotherapists, ergonomists, technology designers, and public health specialists may optimize prevention and management strategies at individual and population levels.

Conclusion

This investigation provides compelling evidence that habitual smartphone use is associated with substantial alterations in dynamic spinal load distribution during functional movement tasks, extending beyond previously documented static postural changes. Heavy smartphone users demonstrated significantly reduced lumbar contribution to trunk flexion (38% *vs.* 52% in controls), compensatory pelvic motion dominance, compromised trunk control quality, and markedly degraded dynamic postural stability during reaching tasks. These alterations appear to represent centrally-mediated motor control adaptations rather than simple mechanical constraints, as they persist during activities performed without smartphone interaction.

The dose-response relationships observed between smartphone usage duration and biomechanical alterations strengthen arguments for causal linkage and suggest potential thresholds for risk stratification. The significant improvements following a six-week movement re-patterning and trunk stabilization intervention demonstrate modifiability of these alterations, providing optimism for therapeutic management. However, incomplete normalization suggests that prevention may be preferable to remediation, highlighting the importance of public awareness regarding postural consequences of smartphone behaviors.

From a broader perspective, these findings illustrate how ubiquitous technological tools can fundamentally influence human movement patterns and motor control organization. As smartphone adoption continues expanding globally, understanding and addressing biomechanical consequences becomes increasingly relevant for musculoskeletal health promotion. The integration of ergonomic design principles in technology development, public education regarding postural implications, and evidence-based movement interventions for high-use populations represent complementary strategies for mitigating potential adverse effects of this pervasive technology on human biomechanics and movement health.

Future research should examine long-term clinical consequences of observed biomechanical alterations, optimal intervention protocols for maximizing movement pattern restoration, and preventive strategies applicable at population levels. Understanding mechanisms underlying motor control adaptations through neurophysiological investigations would enhance intervention design and potentially reveal broader principles regarding how sustained postural exposures influence motor system organization. Ultimately, this line of inquiry contributes to the fundamental understanding of how environmental factors—including technological tools that have become integral to modern life—shape human movement patterns, motor control strategies, and musculoskeletal health outcomes.

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