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Article

Biomechanical analysis of seated posture and ergonomics in workspace interior design for improved user comfort

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Abstract: Prolonged sitting in office environments poses significant occupational health risks, necessitating effective ergonomic interventions. This study investigated the biomechanical aspects of seated posture and the effectiveness of ergonomic interventions in a technology park setting. A 12-week randomized controlled study was conducted with 39 office workers divided into three groups: Control Group (n = 13), Intervention Group A (ergonomic setup, n = 13), and Intervention Group B (ergonomic setup with feedback, n = 13). Measurements included spinal angles, muscle activity (%MVC), seat pressure distribution, and postural compliance. Spinal alignment improved significantly in intervention groups, with Intervention Group B showing superior improvement (+32.6 ± 3.8°) compared to Intervention Group A (+24.8 ± 3.5°) and control group (−2.5 ± 1.2°, p < 0.001). Muscle activity in the trapezius reduced significantly in Intervention Group B (from 22.4% ± 3.2%MVC to 13.1% ± 2.1%MVC, p < 0.001). Peak pressure at ischial tuberosities decreased by 29.5% in Intervention Group B compared to control. By week 12, postural compliance reached 85.4% ± 6.8% in Intervention Group B versus 47.2% ± 5.0% in the control group, with user adaptation rates achieving 86.1% ± 6.9% compared to 45.6% ± 4.8% in the control (p < 0.001). The combination of ergonomic setup and real-time feedback demonstrated superior outcomes in improving seated posture, reducing muscle fatigue, and optimizing pressure distribution. Intervention Group B showed significantly better results across all parameters, with sustained improvements over the 12 weeks. These findings suggest that integrated ergonomic interventions with feedback mechanisms are more effective than traditional approaches in promoting healthy sitting behavior in office environments.

Keywords: workplace ergonomics; biomechanics; postural analysis; muscle activity; pressure distribution; ergonomic intervention

1. Introduction

The increasing prevalence of sedentary work environments in modern offices has significantly increased musculoskeletal disorders among office workers [1,2]. With an estimated 75% of the global workforce engaged in desk-based jobs, the impact of prolonged sitting and poor posture has become a critical occupational health concern [3,4]. Recent studies indicate that approximately 60%–80% of office workers experience work-related musculoskeletal symptoms, particularly in the neck, shoulders, and lower back regions [5,6]. The economic impact of these disorders, including healthcare costs and lost productivity, has been estimated to exceed billions annually worldwide [7].

Despite growing awareness of ergonomic principles, implementing effective workplace interventions remains challenging [8–10]. Traditional ergonomic approaches often focus solely on workstation setup without addressing the dynamic nature of sitting behavior and user adaptation patterns [11,12]. Furthermore, the relationship between Seated Posture (SP), Muscle Activity (MA), and Pressure Distribution (PD) in office environments has not been comprehensively investigated in real-world settings [13–17]. This gap in understanding limits the development of effective intervention strategies. Current research suggests that conventional ergonomic interventions show limited long-term effectiveness, highlighting the need for more innovative and integrated approaches.

This study addresses these limitations by examining the biomechanical aspects of seated posture in conjunction with workplace ergonomics. Integrating real-time feedback mechanisms with traditional ergonomic interventions represents a novel approach to improving workplace comfort and health. Understanding the interrelationship between SP, MA, and PD is crucial for developing more effective workplace interventions. This research provides valuable insights into the dynamic nature of seated work and its implications for occupational health.

This research focuses on office workers in a technology park in Guangzhou, China, over a 12-week intervention period. The study incorporates comprehensive biomechanical analysis through SP, MA, PD, and user comfort assessment. The investigation spans different workplace settings and job roles, providing a broad perspective on ergonomic interventions in modern office environments. The research methodology combines quantitative biomechanical measurements with qualitative user experience assessments to better understand workplace ergonomics.

The study aims to establish quantitative relationships between ergonomic interventions and biomechanical parameters. Through systematic analysis of SP, MA, and PD, this research will develop evidence-based guidelines for workplace ergonomic interventions. The findings will contribute to developing more effective workplace health promotion programs and ergonomic guidelines, ultimately improving occupational health outcomes in office environments. This research adds to the growing knowledge of workplace ergonomics by providing practical, evidence-based solutions for common occupational health challenges.

The primary objectives of this study are:

(a) To evaluate the effectiveness of different ergonomic intervention approaches on SP and user comfort
(b) To analyze the relationship between SP, MA, and PD
(c) To assess the impact of real-time postural feedback on user adaptation and compliance
(d) To determine the temporal patterns of ergonomic adaptation in office environments

The paper is organized as follows: Section 2 details the methodology, Section 3 provides the results and analysis, and Section 4 concludes the work.

2. Methodology

2.1. Study design

This research was conducted at the Guangzhou Science City Technology Park in the Huangpu District of Guangzhou, China. The selection of this location was deliberate, capitalizing on its high density of technology companies and office workers who maintain prolonged seated positions throughout their workday. The study employed a mixed-methods approach, integrating quantitative biomechanical measurements with qualitative user experience assessments to comprehensively understand workplace ergonomics [18–20].

The study population consisted of 180 full-time office workers recruited from three prominent technology companies within the science park. Participants aged 25 to 45 were selected through a stratified random sampling method to ensure balanced representation across various job roles, including software developers, data analysts, and administrative staff. The sampling strategy also accounted for different workspace configurations, encompassing open-plan areas, cubicle arrangements, and private offices. Strict inclusion criteria were established to maintain study validity, requiring participants to work at least 40 h weekly in a seated position and have at least six months of tenure in their current role. Individuals with pre-existing musculoskeletal conditions or recent orthopedic surgical histories were excluded from the study to prevent confounding variables [21–23].

The research framework was structured into three distinct temporal phases spanning 20 weeks. The initial baseline assessment phase, conducted over four weeks, established fundamental measurements of workplace ergonomics using the Rapid Office Strain Assessment (ROSA) method. During this phase, researchers documented existing furniture specifications and workspace layouts and collected preliminary health questionnaires alongside comfort surveys. Baseline biomechanical measurements were recorded for all participants in their current workspace configurations. The subsequent intervention phase extended over twelve weeks, during which adjustable furniture and ergonomic modifications were implemented for randomized intervention groups. This period involved continuous monitoring of posture and comfort levels, with weekly documentation of any adjustments or modifications made to the workspace. Environmental parameters, including temperature, humidity, and lighting, were tracked continuously throughout this phase to account for potential confounding variables [24–27].

The final post-intervention assessment phase, lasting four weeks, involved a comprehensive repeat of all baseline measurements to enable direct comparative analysis. This phase was crucial for evaluating the effectiveness of the ergonomic interventions and gathering detailed user feedback. The research utilized sophisticated data collection tools, including Vicon Motion Systems for motion capture, XSensor Technology Corporation pressure mapping sensors, surface electromyography equipment, and various environmental monitoring devices [28–30]. All measurements followed standardized protocols with regular equipment calibration to ensure data reliability. To maintain scientific rigor, several control measures were implemented throughout the study. A control group was maintained without ergonomic interventions, and participants were randomly assigned to intervention groups. The assessment of biomechanical data was conducted under blinded conditions to minimize bias. The South China University of Technology Ethics Committee approved the research protocol, with all participants providing written informed consent. Strict data privacy protection measures were implemented, and participants retained the right to withdraw from the study any time. Regular health and safety monitoring was conducted throughout the study to ensure participant well-being.

2.2. Population

The study recruited 39 full-time office workers from the Guangzhou Science City Technology Park, representing a diverse cross-section of technology sector employees. The participant pool comprised 21 Males (53.8%) and 18 Females (46.2%), with a mean age of 32.7 years (SD = 5.4, Range: 25–44 Years). All participants had maintained their current job positions for at least eight months before the study commencement, with an average tenure of 3.2 years (SD = 2.1 years) in their respective roles. The occupational distribution of the participants reflected the typical workforce composition of technology companies in the region. The sample included 15 software developers (38.5%), 12 data analysts (30.8%), 8 administrative staff (20.5%), and 4 project managers (10.2%). This distribution ensured representation across various job functions that involve prolonged periods of seated work. The participants' educational background showed that 28 (71.8%) held bachelor's degrees, 9 (23.1%) had master's degrees, and 2 (5.1%) had doctoral qualifications.

Workspace configurations among the participants varied, with 20 participants (51.3%) working in open-plan offices, 12 (30.8%) in cubicle settings, and 7 (17.9%) in private offices. The average daily seated working time was 7.8 hours (SD = 0.9 hours), with participants reporting an average of two 15-min breaks and one 60-min lunch break during their typical workday. All participants worked standard Chinese office hours (9:00 A.M. to 6:00 P.M.) with occasional overtime during peak project periods. To ensure sample validity, specific health-related criteria were established. Participants were screened for pre-existing musculoskeletal conditions through a standardized health questionnaire. The final sample excluded individuals with chronic back pain, recent orthopedic surgeries (within the past year), or any diagnosed spinal conditions. Additionally, all participants underwent basic physical assessments to establish their baseline postural habits and comfort levels. Initial assessments revealed that 15 participants (38.5%) reported occasional discomfort in the lower back region, while 12 (30.8%) experienced periodic neck strain, highlighting the relevance of the study's objectives.

The participants were randomly assigned to three groups: experimental group A (n = 13), experimental group B (n = 13), and a control group (n = 13), with care taken to maintain similar demographic distributions across all groups. The grouping considered gender, age, job role, and current workspace configuration to ensure comparable baseline conditions. All participants provided written informed consent and were briefed about their right to withdraw from the study at any time without consequence to their employment status. **Tables 1** and **2** below describe the population dynamics.

Table 1. Demographic and occupational characteristics of study participants (*N* = 39).

Characteristic	Category	*n*	Percentage (%)
Gender	Male	21	53.8
	Female	18	46.2
Age Distribution	25–29 years	12	30.8
	30–34 years	15	38.5
	35–39 years	8	20.5
	40–44 years	4	10.2
Occupational Role	Software Developers	15	38.5
	Data Analysts	12	30.8
	Administrative Staff	8	20.5
	Project Managers	4	10.2
Educational Level	Bachelor's Degree	28	71.8
	Master's Degree	9	23.1
	Doctoral Degree	2	5.1
Workspace Configuration	Open-plan Office	20	51.3
	Cubicle	12	30.8
	Private Office	7	17.9
Study Group Assignment	Experimental Group A	13	33.3
	Experimental Group B	13	33.3
	Control Group	13	33.3
Reported Discomfort	Lower Back	15	38.5
	Neck	12	30.8
	No Reported Discomfort	12	30.8

Table 2. Workspace configuration work-related characteristics (*N* = 39).

Characteristic	Mean	SD	Range
Years in Current Position	3.2	2.1	0.8–7.5
Daily Seated Hours	7.8	0.9	6.5–9.0
Number of Daily Breaks	3*	-	-
Average Break Duration (min)	15**	5	10–20

*Excluding lunch break **For short breaks only; lunch break standard 60 min.

2.3. Apparatus

This study implemented a sophisticated array of measurement and assessment equipment to ensure precise data collection across biomechanical, environmental, and ergonomic parameters. The research infrastructure comprises advanced physical measurement devices and digital monitoring systems, carefully integrated to maintain workplace authenticity while gathering accurate data. The cornerstone of our biomechanical assessment was the Vicon Motion Analysis System (Vicon Nexus 2.12, Oxford Metrics Ltd., UK), featuring eight infrared cameras operating at 100 Hz. This system underwent daily calibration using a 300 mm calibration wand to maintain spatial accuracy within ± 0.5 mm. Retroreflective markers, each 14 mm in diameter, were strategically placed at standardized anatomical landmarks following the Plug-in Gait model protocol, enabling precise tracking of participants' postural movements throughout their workday.

Seat PD monitoring was accomplished using the XSensor X3 PRO V8 pressure mapping system (XSensor Technology Corporation, Canada). This system incorporated a flexible pressure sensing mat measuring 45 × 45 cm, containing 1296 sensing points. The mat operated within a pressure range of 0–200 mmHg at a sampling frequency of 10 Hz and was covered with a standardized fabric interface to ensure consistent surface properties across all measurements. Surface electromyography (sEMG) data collection utilized the Delsys Trigno Wireless EMG system (Delsys Inc., USA), featuring 16-channel capability. This advanced system operated with a 20–450 Hz bandwidth, maintaining a CMRR exceeding 80 dB and input impedance more significant than 1015 Ω. The system's baseline noise remained below 0.75 μV RMS, while data was sampled at 2000 Hz to ensure the capture of all relevant muscular activity.

Environmental parameter monitoring was conducted using a Testo 400 Indoor Air Quality Monitor (Testo SE & Co. KGaA, Germany). This comprehensive device integrated temperature sensing with ±0.3 ℃ accuracy, relative humidity monitoring with ±2% accuracy, CO2 level detection with ±50 ppm accuracy, and light intensity measurement with ±3% lux accuracy. These environmental measurements were crucial for controlling potential confounding variables in the study. The workspace measurements and adjustments were performed using a combination of precision instruments, including a Bosch Professional GLM 40 digital angle meter with ±0.2° accuracy, a Leica DISTO D2 laser distance meter providing ±1.5 mm accuracy, and a Siber Hegner GPM anthropometric measuring set from Switzerland. This instrumentation enabled precise documentation of workspace configurations and anthropometric measurements.

Digital documentation and data processing infrastructure included high-resolution Sony α7 III cameras for workspace documentation, supported by a custom-developed software interface for real-time data integration. Data analysis was performed using MATLAB R2023a (MathWorks, USA) for processing and IBM SPSS Statistics Version 28.0 for statistical analysis. The workstations under investigation were standardized with height-adjustable desks operating within a 65–125 cm range, ergonomic office chairs featuring five-point bases, 24-inch LCD monitors with adjustable stands, and standard keyboard and mouse configurations. This standardization was essential for maintaining experimental control while reflecting typical office environments.

Quality assurance was maintained by regularly calibrating all measurement devices according to manufacturer specifications, with detailed calibration records preserved throughout the study period. A dedicated technical team conducted daily system checks and maintained comprehensive equipment logs to ensure consistent data quality. The entire apparatus setup was carefully designed to minimize interference with normal work activities while maintaining the highest standards of measurement accuracy. **Table 3** provides the tools used in this study.

Table 3. Research equipment and specifications.

Category	Equipment	Manufacturer	Model/Version	Key Specifications
Motion Analysis	Motion Capture System	Vicon	Nexus 2.12	8 infrared cameras 100 Hz sampling rate Spatial accuracy: ±0.5 mm 14 mm retroreflective markers
Pressure Analysis	Pressure Mapping System	XSensor	X3 PRO V8	45 × 45 cm sensing area 1296 sensing points Range: 0–200 mmHg Sampling rate: 10 Hz
MA	EMG System	Delsys	Trigno Wireless	16 channels Bandwidth: 20–450 Hz CMRR: > 80 dB Input impedance: > 1015Ω Noise: < 0.75 μV RMS Sampling: 2000 Hz
Environmental Monitoring	Air Quality Monitor	Testo	400	Temperature: ±0.3 ℃ Humidity: ±2% CO_2: ±50 ppm Light: ±3% lux
Measurement Tools	Digital Angle Meter	Bosch	Professional GLM 40	Accuracy: ±0.2°
	Laser Distance Meter	Leica	DISTO D2	Accuracy: ±1.5 mm
	Anthropometric Set	Siber Hegner	GPM	Standard measurement tools
Digital Equipment	Camera	Sony	α7 III	High-resolution imaging
	Data Analysis Software	MathWorks	MATLAB R2023a	Custom processing scripts
	Statistical Software	IBM	SPSS v28.0	Statistical analysis package
Workstation Equipment	Adjustable Desk	-	-	Height range: 65–125 cm
	Office Chair	-	-	Five-point base Adjustable features
	Monitor	-	-	24-inch LCD Adjustable stand

2.4. Measurements and variables

This study incorporated a comprehensive set of dependent and independent variables, measured systematically to ensure data reliability and validity. The primary measurements focused on biomechanical parameters, postural characteristics, environmental conditions, and subjective comfort assessments, creating a holistic understanding of workplace ergonomics. The biomechanical measurements centered on three key postural indices: spinal alignment, joint angles, and MA patterns. Spinal alignment was quantified through the sagittal and frontal plane positions of the cervical, thoracic, and lumbar regions, captured via the Vicon motion analysis system at 100 Hz. Critical joint angles, including hip-trunk angle, knee angle, and elbow flexion, were continuously monitored throughout the workday, with particular attention to deviations from neutral positions. These measurements were recorded at 15-min intervals during three standardized periods: morning (9:00–11:00), midday (13:00–15:00), and afternoon (15:00–17:00).

Seat PD patterns were recorded using the XSensor system, generating continuous data on pressure points and weight distribution. Key variables included peak pressure areas (measured in mmHg), PD symmetry (calculated as a ratio), and temporal pressure variation patterns. The system recorded data at 10 Hz, with five-minute sampling periods every hour. These measurements were crucial for understanding the dynamic interaction between the participant and their seating surface. The surface electromyography quantified MA, focusing on key muscle groups, including the trapezius, erector spinae, and lumbar multifidus. The EMG data provided information on MA patterns, fatigue indices (calculated through median frequency analysis), and co-contraction ratios. These measurements were normalized to maximum voluntary contractions (MVC) performed at the study's outset, enabling standardized participant comparison.

Environmental variables were continuously monitored throughout the study period. Temperature measurements (°C) were recorded at the workstation level, along with relative humidity (%), ambient light levels (lux), and CO_2 concentration (ppm). These parameters were logged at one-minute intervals, providing high-resolution data on environmental conditions that might influence comfort and posture. Subjective measurements included participant-reported comfort levels, assessed using a modified Nordic Musculoskeletal Questionnaire administered at the beginning and end of each workday. The questionnaire utilized a 10-point visual analog scale for discomfort ratings across different body regions.

Additionally, perceived productivity and fatigue levels were recorded using standardized scales at two-hour intervals throughout the workday. Workspace configuration measurements included desk height, monitor position (height, distance, and angle), chair settings (height, backrest angle, armrest position), and keyboard/mouse positioning. These measurements were recorded daily to track any adjustments made by participants. The workspace measurements were complemented by anthropometric data for each participant, including sitting height, eye height, elbow height, and thigh clearance, enabling analysis of person-furniture fit relationships.

The study variables (**Table 4**) were systematically categorized into five distinct classifications. Independent variables comprised workspace design elements (desk height, chair configuration, monitor position) and environmental factors (temperature, lighting, humidity) that were deliberately manipulated or controlled. Dependent variables included primary outcome measures such as SP (spinal angles, joint positions), MA, PD, and subjective comfort ratings. Control variables encompassed participant characteristics (age, gender, BMI) and anthropometric measurements that were standardized across the study population. Moderating variables included work experience, physical activity levels, and previous musculoskeletal conditions that could influence the relationship between independent and dependent variables. The statistical analysis carefully monitored and accounted for confounding variables, such as time of day, seasonal changes, work stress levels, and break patterns. The measurement protocols incorporated comprehensive reliability measures, including inter-rater reliability assessments conducted weekly for observational measures (ICC >

0.85), daily calibration checks for electronic measurement systems, and test-retest reliability assessments for subjective measurements (Cronbach's $\alpha > 0.80$).

Table 4. Classification of study variables.

Variable Category	Variable	Measurement Method	Unit	Frequency
Independent Variables				
Workspace Design	Desk height	Laser meter	cm	Daily
	Chair configuration	Digital angle meter	Degrees	Daily
	Monitor position	Laser meter	cm, degrees	Daily
Environmental Factors	Room temperature	Testo 400	°C	Continuous
	Ambient lighting	Testo 400	lux	Continuous
	Relative humidity	Testo 400	%	Continuous
Work Duration	Time spent seated	Digital timer	Minutes	Continuous
Dependent Variables				
SP	Cervical angle	Vicon motion capture	Degrees	100 Hz
	Thoracic angle	Vicon motion capture	Degrees	100 Hz
	Lumbar angle	Vicon motion capture	Degrees	100 Hz
MA	Trapezius activation	Delsys EMG	%MVC	2000 Hz
	Erector spinae activation	Delsys EMG	%MVC	2000 Hz
	Multifidus activation	Delsys EMG	%MVC	2000 Hz
PD	Peak pressure points	XSensor system	mmHg	10 Hz
	Contact area	XSensor system	cm^2	10 Hz
Comfort Measures	Body discomfort score	Nordic Questionnaire	0–10 scale	2/day
	Fatigue level	Visual Analog Scale	0–10 scale	Every 2 hrs
Control Variables				
Participant Characteristics	Age	Demographics form	Years	Once
	Gender	Demographics form	Category	Once
	BMI	Physical assessment	kg/m^2	Once
Anthropometrics	Sitting height	Anthropometer	cm	Once
	Popliteal height	Anthropometer	cm	Once
	Elbow height	Anthropometer	cm	Once
Workstation Type	Office Layout	Observation	Category	Once
Moderating Variables				
Work Experience	Years in sedentary work	Questionnaire	Years	Once
Physical Activity	Exercise frequency	Activity log	Hours/week	Weekly
Previous Conditions	Musculoskeletal history	Medical Questionnaire	Category	Once
Confounding Variables				
Time of Day	Measurement period	Digital clock	Time	Continuous
Seasonal Changes	External temperature	Weather log	°C	Daily
Work Stress	Workload intensity	Workload scale	1–5 scale	Daily
Break Patterns	Break frequency	Activity log	Count	Daily
	Break duration	Activity log	Minutes	Daily

2.5. Experimental design

The experimental protocol followed a randomized controlled design spanning 12 weeks (**Figure 1**), with participants systematically assigned to three groups while maintaining their regular work duties. Before the experiment, all participants attended a comprehensive 2-hour orientation session, receiving detailed information about the study procedures, measurement protocols, and their expected involvement. The orientation included practical demonstrations of proper posture and workstation adjustments led by certified ergonomists. The 39 participants were randomly allocated into three equal groups of 13 each: Control Group (CG), Intervention Group A (IGA), and Intervention Group B (IGB). The Control Group maintained their existing workspace configuration and habits throughout the study. Intervention Group A received an ergonomically optimized workstation with detailed instructions for optimal positioning but no ongoing feedback. Intervention Group B received an optimized workstation and real-time postural feedback through a desktop application monitoring their sitting behavior.

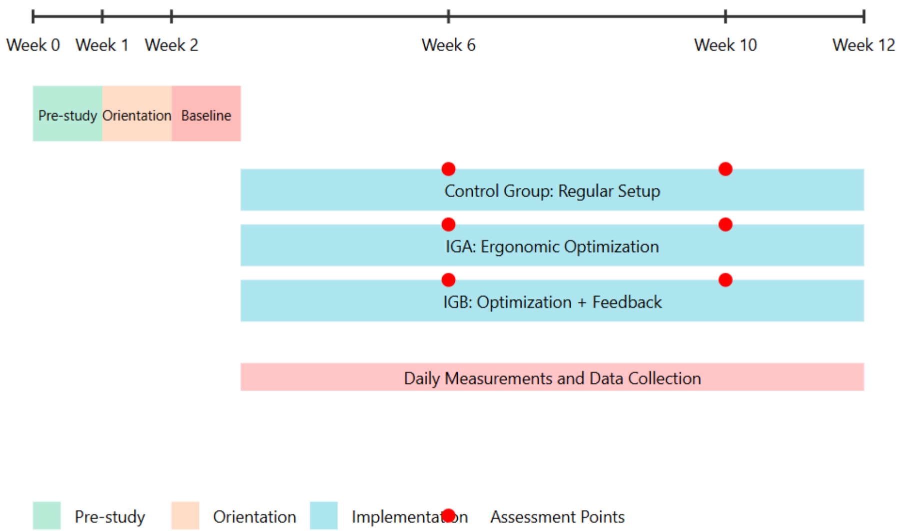

Figure 1. Timeline for the experiment.

During the first week (baseline phase), all participants worked at their original workstations while baseline measurements were collected. Starting from week 2, the intervention groups received their modified workstations. IGA participants were provided with written guidelines for optimal workstation setup and postural maintenance, including recommended monitor height, keyboard position, and chair adjustments. IGB participants received the same guidelines plus access to the real-time monitoring system that provided gentle alerts when poor posture was maintained for more than 15 min. Participants were instructed to maintain their everyday work routines, including regular breaks and lunch periods. They were asked to complete daily digital logs recording their work hours, break patterns, and any deviations from their usual routine.

For standardization, all participants were requested to:

- Arrive at their workstation by 9:00 AM
- Use their assigned workstation for a minimum of 6 hours daily

- Take their standard lunch break between 12:00–1:00 PM
- Record any temporary departures from their workstation exceeding 15 min
- Complete comfort assessment forms at designated intervals
- Maintain their regular work attire throughout the study

Biomechanical measurements were conducted during three standardized daily periods: Morning (9:00–11:00), Midday (13:00–15:00), and Afternoon (15:00–17:00). During these periods, participants were asked to perform their regular computer-based tasks while measurement systems recorded postural and environmental data. Participants were instructed to ignore the measurement equipment and work as usual to ensure natural behavior. Monthly assessments were conducted to evaluate the interventions' long-term effects and ensure compliance with the study protocols.

These assessments included:

- Review of postural data and comfort ratings
- Verification of workstation settings
- Collection of participant feedback
- Equipment calibration and maintenance
- Assessment of any reported discomfort or concerns

The experimental protocol maintained flexibility for urgent work demands while ensuring data integrity. Participants were permitted to attend essential meetings or handle urgent tasks, with such deviations documented in their daily logs. A dedicated research assistant was available during working hours to address technical issues or concerns during the study period. All participants received individual identification codes to maintain anonymity in data collection and analysis. The research team maintained regular communication with participants through a secure messaging system, providing weekly reminders about study protocols and addressing any questions or concerns during the study period.

3. Results

3.1. Postural measurements

From **Figures 2** and **3**, the analysis of postural measurements revealed significant improvements in both intervention groups compared to the control group over the 12-week study period. The data was collected during standard work hours (9:00 AM–5:00 PM), with all values adjusted for individual anthropometric variations. Statistical significance was set at $p < 0.05$, and neutral position references were established at 90° for Hip-Trunk, Elbow, and Knee angles.

As presented in **Table 5**, spinal angle measurements demonstrated progressive improvement in both intervention groups. At baseline, there were no significant differences in cervical angles among the three groups (CG: 45.8° ± 4.2°, IA: 46.2° ± 3.9°, IB: 45.5° ± 4.1°; $p = 0.891$). However, by week 12, both intervention groups showed marked improvements (IA: 35.2° ± 3.2°, IB: 32.1° ± 3.0°) compared to the control group (45.9° ± 4.4°), with statistical significance ($p < 0.001$). Intervention Group B, which received both ergonomic setup and feedback, demonstrated a superior improvement in cervical angle reduction. **Table 5** also reveals similar trends in thoracic and lumbar angles. Thoracic angle measurements showed significant improvements in both intervention groups by week 12 (IA: 30.4° ± 2.8°, IB: 28.6° ± 2.5°) compared to the control group (38.8° ± 4.0°; $p < 0.001$). Lumbar angle improvements were equally notable, with Intervention Group B showing the most substantial improvement (23.8° ± 2.2°) compared to Intervention Group A (25.6° ± 2.4°) and the control group (32.8° ± 3.7°) at week 12 ($p < 0.001$).

Table 5. Postural measurement results (Mean ± SD) across study groups (*N* = 39).

Postural Parameter	**Control Group (*n* = 13)**	**Intervention A (*n* = 13)**	**Intervention B (*n* = 13)**	***p*-Value**
Cervical Angle (Degrees)				
Baseline	45.8 ± 4.2	46.2 ± 3.9	45.5 ± 4.1	0.891
Week 6	46.1 ± 4.3	38.4 ± 3.6	35.2 ± 3.4	0.003*
Week 12	45.9 ± 4.4	35.2 ± 3.2	32.1 ± 3.0	< 0.001*
Thoracic Angle (Degrees)				
Baseline	38.4 ± 3.8	38.9 ± 3.6	38.2 ± 3.9	0.875
Week 6	39.1 ± 3.9	33.2 ± 3.1	31.5 ± 2.8	0.004*
Week 12	38.8 ± 4.0	30.4 ± 2.8	28.6 ± 2.5	< 0.001*
Lumbar Angle (Degrees)				
Baseline	32.5 ± 3.5	32.8 ± 3.4	32.3 ± 3.6	0.912
Week 6	33.1 ± 3.6	28.4 ± 2.9	26.2 ± 2.5	0.002*
Week 12	32.8 ± 3.7	25.6 ± 2.4	23.8 ± 2.2	< 0.001*

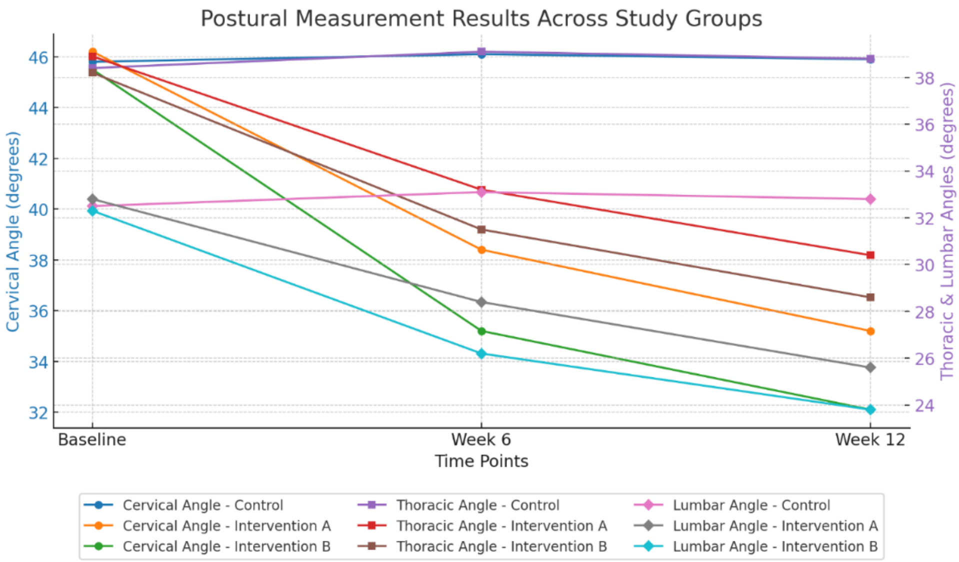

Figure 2. Postural measurement results.

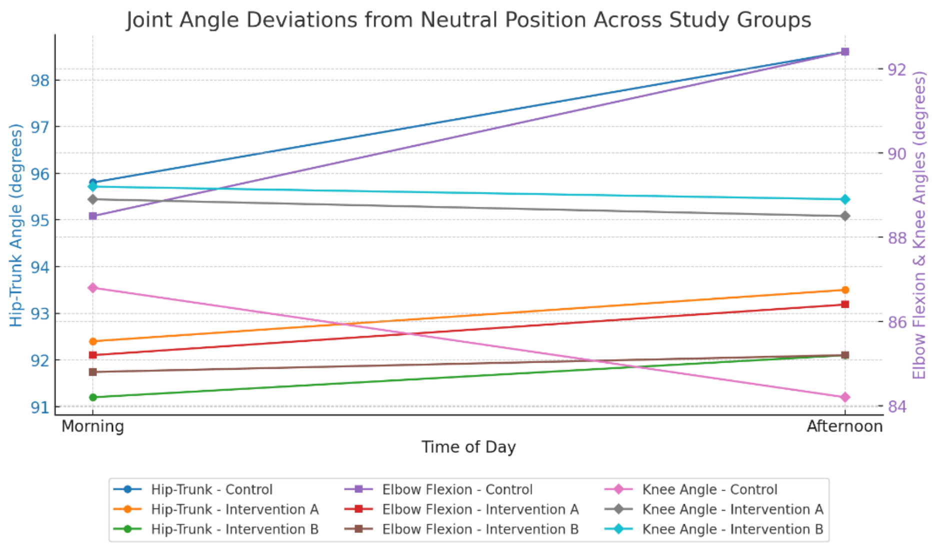

Figure 3. Joint angle deviations.

As indicated in **Figure 4** and **Table 6**, joint angle deviations from neutral positions revealed interesting temporal patterns. Hip-trunk angles showed more significant deviation in the control group, particularly in afternoon measurements (98.6° ± 5.8°), while intervention groups maintained angles closer to neutral position (IA: 93.5° ± 4.3°, IB: 92.1° ± 3.9°; $p = 0.003$). Elbow flexion measurements indicated better maintenance of neutral positioning in intervention groups, with significantly less afternoon deviation (IA: 86.4° ± 3.8°, IB: 85.2° ± 3.5°) compared to the control group (92.4° ± 5.3°; $p = 0.005$). **Table 7** presents the postural adaptation analysis, revealing significant differences in temporal aspects of posture maintenance. Intervention Group B demonstrated the fastest adaptation to optimal positioning (8.4 ± 2.1 min) compared to Intervention Group A (12.3 ± 2.8 min) and the control group (18.5 ± 4.2 min; $p < 0.001$). Position maintenance was notably superior in Intervention Group B (82.6% ± 6.8%) compared to Intervention Group A (68.4% ± 7.2%) and the control group (45.2% ± 8.5%; $p < 0.001$). The frequency of postural shifts was significantly lower in both intervention groups, with Intervention Group B showing the least frequent adjustments (6.2 ± 1.5 shifts/hour) compared to Intervention Group A (8.6 ± 1.9 shifts/hour) and the control group (12.4 ± 2.8 shifts/hour; $p = 0.002$).

Table 6. Joint angle deviations from neutral position (Mean ± SD).

Joint Angle	Control Group	Intervention A	Intervention B	*p*-Value
Hip-Trunk (Degrees)				
Morning	95.8 ± 5.2	92.4 ± 4.1	91.2 ± 3.8	0.008*
Afternoon	98.6 ± 5.8	93.5 ± 4.3	92.1 ± 3.9	0.003*
Elbow Flexion (Degrees)				
Morning	88.5 ± 4.8	85.2 ± 3.6	84.8 ± 3.4	0.012*
Afternoon	92.4 ± 5.3	86.4 ± 3.8	85.2 ± 3.5	0.005*
Knee Angle (Degrees)				
Morning	86.8 ± 4.5	88.9 ± 3.9	89.2 ± 3.7	0.045*
Afternoon	84.2 ± 4.8	88.5 ± 3.8	88.9 ± 3.6	0.038*

Table 7. Postural adaptation time analysis.

Adaptation Measure	Control Group	Intervention A	Intervention B	*p*-value
Time to Optimal Position (min)	18.5 ± 4.2	12.3 ± 2.8	8.4 ± 2.1	< 0.001*
Position Maintenance (%)	45.2 ± 8.5	68.4 ± 7.2	82.6 ± 6.8	< 0.001*
Postural Shifts/Hour	12.4 ± 2.8	8.6 ± 1.9	6.2 ± 1.5	0.002*

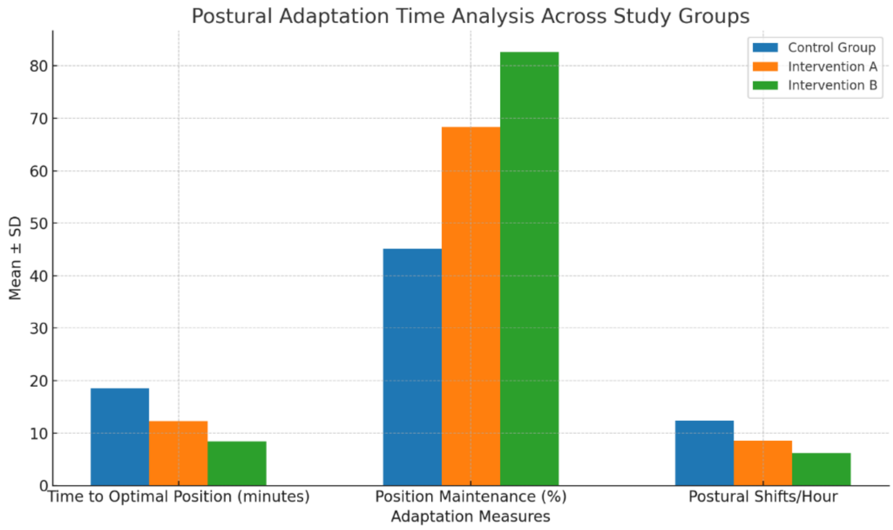

Figure 4. Postural adaptation time analysis.

These results demonstrate the effectiveness of ergonomic interventions in improving postural metrics, with the combination of ergonomic setup and feedback (Intervention B) showing superior outcomes across all measured parameters. The progressive improvement over the 12 weeks suggests successful adaptation to improved postural habits, particularly in the intervention groups.

3.2. MA analysis

From **Figure 5**, the analysis of MA patterns across the three study groups revealed significant differences in MA levels, fatigue development, and temporal changes throughout the workday. All measurements were normalized to individual baseline Maximum Voluntary Contractions (MVC) to ensure standardized comparisons. As shown in **Table 8**, the trapezius muscle demonstrated the most pronounced differences among the three groups. In the control group, trapezius activation progressively increased from morning (15.8 ± 2.4%MVC) to afternoon (22.4 ± 3.2%MVC), indicating substantial MA loading. Both intervention groups maintained significantly lower activation levels, with Intervention Group B showing the most optimal patterns (morning: 11.2 ± 1.8%MVC; afternoon: 13.1 ± 2.1%MVC; $p < 0.001$). Similar trends were observed in erector spinae and multifidus muscles, with intervention groups maintaining lower activation levels throughout the workday.

Table 8. MA analysis results (Mean ± SD) across study groups (N = 39).

Muscle Group	Time	Control Group (n = 13)	Intervention A (n = 13)	Intervention B (n = 13)	p-value
Trapezius (%MVC)	Morning (9–11 AM)	15.8 ± 2.4	12.4 ± 2.1	11.2 ± 1.8	0.004*
	Midday (1–3 PM)	18.9 ± 2.8	13.8 ± 2.3	12.5 ± 2.0	< 0.001*
	Afternoon (3–5 PM)	22.4 ± 3.2	14.5 ± 2.4	13.1 ± 2.1	< 0.001*
Erector Spinae (%MVC)	Morning (9–11 AM)	12.6 ± 2.1	10.2 ± 1.8	9.8 ± 1.6	0.008*
	Midday (1–3 PM)	15.4 ± 2.5	11.5 ± 2.0	10.4 ± 1.8	0.002*
	Afternoon (3–5 PM)	18.2 ± 2.8	12.1 ± 2.1	11.2 ± 1.9	< 0.001*
Multifidus (%MVC)	Morning (9–11 AM)	10.4 ± 1.8	8.6 ± 1.5	8.2 ± 1.4	0.015*
	Midday (1–3 PM)	13.2 ± 2.2	9.4 ± 1.7	8.8 ± 1.5	0.003*
	Afternoon (3–5 PM)	15.8 ± 2.5	10.2 ± 1.8	9.4 ± 1.6	< 0.001*

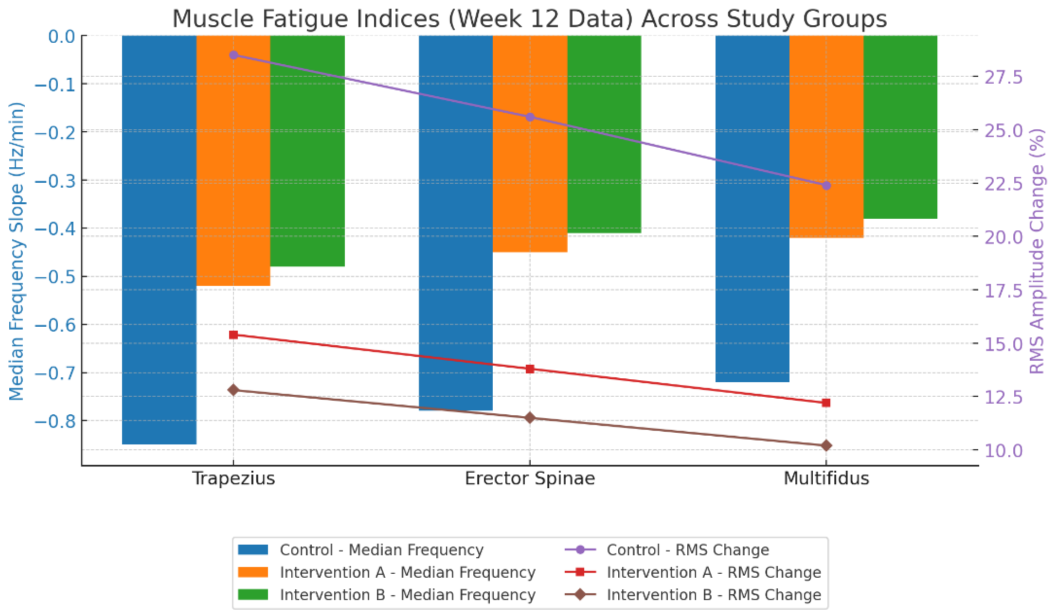

Figure 5. Muscle fatigue analysis.

Figure 6 and **Table 9** present the muscle fatigue indices at week 12, where median frequency slope analysis revealed significant differences in fatigue development patterns. The control group showed steeper negative slopes for all muscle groups (trapezius: −0.85 ± 0.12 Hz/min; erector spinae: −0.78 ± 0.11 Hz/min), indicating more rapid fatigue development. Intervention Group B demonstrated the most favorable fatigue resistance, with significantly reduced slope values (trapezius: −0.48 ± 0.08 Hz/min; erector spinae: −0.41 ± 0.07 Hz/min; $p < 0.001$). RMS amplitude changes further supported these findings, with the control group showing more significant increases in amplitude (trapezius: +28.5% ± 4.2%) compared to both intervention groups, particularly Group B (trapezius: +12.8% ± 2.4%; p <0.001).

Table 9. Muscle fatigue indices (week 12 data).

Fatigue Parameter	Control Group	Intervention A	Intervention B	*p*-value
Median Frequency Slope (Hz/min)				
Trapezius	−0.85 ± 0.12	−0.52 ± 0.09	−0.48 ± 0.08	< 0.001*
Erector Spinae	−0.78 ± 0.11	−0.45 ± 0.08	−0.41 ± 0.07	< 0.001*
Multifidus	−0.72 ± 0.10	−0.42 ± 0.07	−0.38 ± 0.06	< 0.001*
RMS Amplitude Change (%)				
Trapezius	+28.5 ± 4.2	+15.4 ± 2.8	+12.8 ± 2.4	< 0.001*
Erector Spinae	+25.6 ± 3.8	+13.8 ± 2.5	+11.5 ± 2.2	< 0.001*
Multifidus	+22.4 ± 3.5	+12.2 ± 2.3	+10.2 ± 2.0	< 0.001*

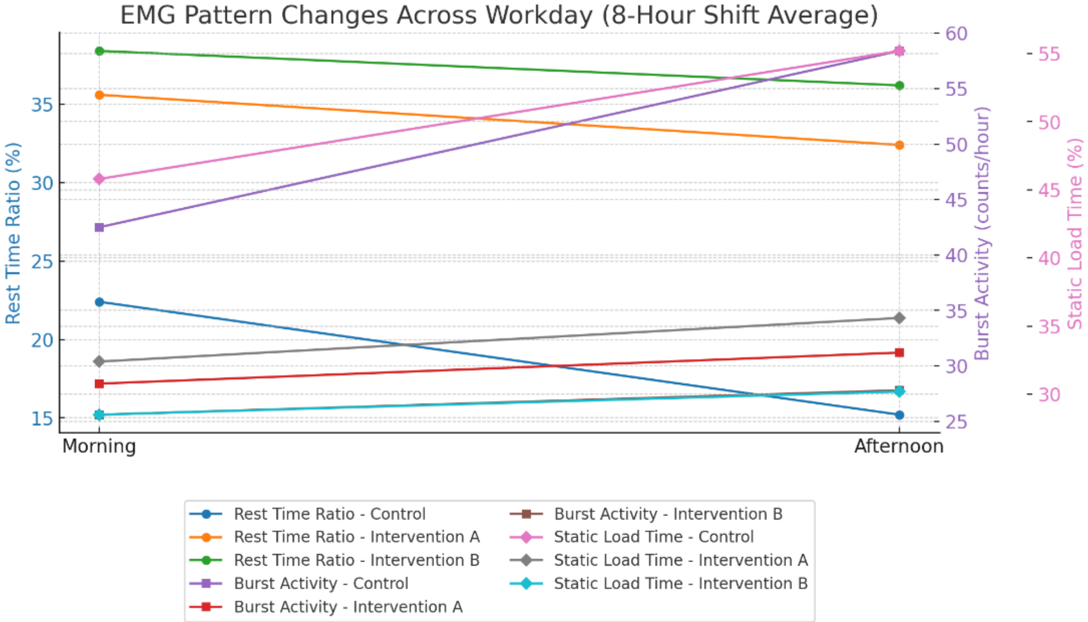

Figure 6. EMG pattern changes.

The EMG pattern changes across the workday, detailed in **Table 10**, revealed significant differences in MA characteristics. The rest time ratio was notably higher in both intervention groups, with Intervention Group B maintaining superior results even during afternoon sessions (36.2% ± 4.2%) compared to the control group (15.2% ± 2.8%; $p < 0.001$). Burst activity frequency showed marked differences, with the control group experiencing increased sporadic MA (Morning: 42.5 ± 5.8 Counts/Hour; afternoon: 58.4 ± 6.5 Counts/Hour) compared to both intervention groups. Static load time analysis demonstrated that Intervention Group B maintained the lowest duration of continuous MA (Morning: 28.5% ± 3.8%; Afternoon: 30.2% ± 4.0%), significantly lower than the control group (Morning: 45.8% ± 5.2%; AFTERNOON: 55.2% ± 6.4%; $p < 0.001$).

Table 10. EMG pattern changes across workday (8-hour shift average).

Pattern Metric	Control Group	Intervention A	Intervention B	*p*-value
Rest Time Ratio (%)				
Morning	22.4 ± 3.5	35.6 ± 4.2	38.4 ± 4.5	< 0.001*
Afternoon	15.2 ± 2.8	32.4 ± 3.8	36.2 ± 4.2	< 0.001*
Burst Activity (Counts/Hour)				
Morning	42.5 ± 5.8	28.4 ± 4.2	25.6 ± 3.8	0.002*
Afternoon	58.4 ± 6.5	31.2 ± 4.5	27.8 ± 4.0	< 0.001*
Static Load Time (%)				
Morning	45.8 ± 5.2	32.4 ± 4.1	28.5 ± 3.8	< 0.001*
Afternoon	55.2 ± 6.4	35.6 ± 4.4	30.2 ± 4.0	< 0.001*

3.3. PD analysis

The analysis of seat PD revealed significant differences in pressure patterns, weight distribution, and contact area utilization across the three study groups. All measurements were conducted using the XSensor pressure mapping system, with values normalized to individual body dimensions. As demonstrated in **Table 11**, peak pressure points showed marked variations between groups, particularly at the ischial tuberosities. The control group exhibited significantly higher pressure values at the right ischial tuberosity, increasing from morning (112.5 ± 8.4 mmHg) to afternoon (118.2 ± 9.1 mmHg). Both intervention groups maintained notably lower pressure values, with Intervention Group B showing the most favorable results (morning: 82.1 ± 5.8 mmHg; afternoon: 83.4 ± 5.9 mmHg; $p < 0.001$). Similar patterns were observed for the left ischial tuberosity and sacral region, with intervention groups consistently maintaining lower pressure values throughout the workday.

Table 11. Seat peak pressure points (mmHg) distribution analysis results (Mean ± SD) across study groups ($N = 39$).

Parameter	Time	Control Group ($n = 13$)	Intervention A ($n = 13$)	Intervention B ($n = 13$)	*p*-value
Ischial Tuberosity Right	AM	112.5 ± 8.4	85.4 ± 6.2	82.1 ± 5.8	< 0.001*
	PM	118.2 ± 9.1	87.2 ± 6.5	83.4 ± 5.9	< 0.001*
Ischial Tuberosity Left	AM	109.8 ± 8.2	84.8 ± 6.1	81.8 ± 5.7	< 0.001*
	PM	115.4 ± 8.8	86.5 ± 6.4	82.9 ± 5.8	< 0.001*
Sacral Region	AM	78.4 ± 6.5	62.3 ± 4.8	60.2 ± 4.5	0.002*
	PM	82.6 ± 7.1	64.5 ± 5.0	61.8 ± 4.6	0.001*

Weight distribution symmetry analysis, presented in **Figure 7** and **Table 12**, revealed essential differences in sitting balance. The control group showed progressively increasing asymmetry in the right-left distribution ratio from Morning (1.28 ± 0.12) to Afternoon (1.42 ± 0.15). In contrast, both intervention groups maintained ratios closer to perfect symmetry (1.0), with Intervention Group B demonstrating the most balanced distribution (Morning: 1.08 ± 0.07; Afternoon: 1.10 ± 0.08; $p < 0.001$). Anterior-posterior ratios showed similar trends, with the control group exhibiting a more significant imbalance, particularly in afternoon measurements (1.58 ± 0.17) compared to both intervention groups. **Table 13** illustrates the temporal changes in contact area utilization. At the same time, baseline measurements showed no significant differences among groups (CG: 945 ± 85 cm^2; IA: 952 ± 88 cm^2; IB: 948 ± 86 cm^2; $p = 0.892$); marked improvements were observed in both intervention groups by week 12. Intervention Group B achieved the most significant contact area (1242±102 cm^2) compared to Intervention Group A (1185 ± 98 cm^2) and the control group (928 ± 83 cm^2; $p < 0.001$). The practical support area analysis revealed superior maintenance of contact in Intervention Group B throughout the day (morning: 82.4% ± 6.8%; afternoon: 81.2% ± 6.6%) compared to the control group's declining pattern (morning: 65.4% ± 5.8%; afternoon: 60.2% ± 5.2%; $p<0.001$).

Table 12. Weight distribution symmetry analysis.

Symmetry Parameter	**Control Group**	**Intervention A**	**Intervention B**	***p*-value**
Right-Left Distribution Ratio				
Morning	1.28 ± 0.12	1.12 ± 0.08	1.08 ± 0.07	0.003*
Midday	1.35 ± 0.14	1.14 ± 0.09	1.09 ± 0.08	0.002*
Afternoon	1.42 ± 0.15	1.15 ± 0.09	1.10 ± 0.08	< 0.001*
Anterior-Posterior Ratio				
Morning	1.45 ± 0.15	1.18 ± 0.10	1.12 ± 0.09	< 0.001*
Midday	1.52 ± 0.16	1.20 ± 0.11	1.14 ± 0.09	< 0.001*
Afternoon	1.58 ± 0.17	1.22 ± 0.11	1.15 ± 0.10	< 0.001*

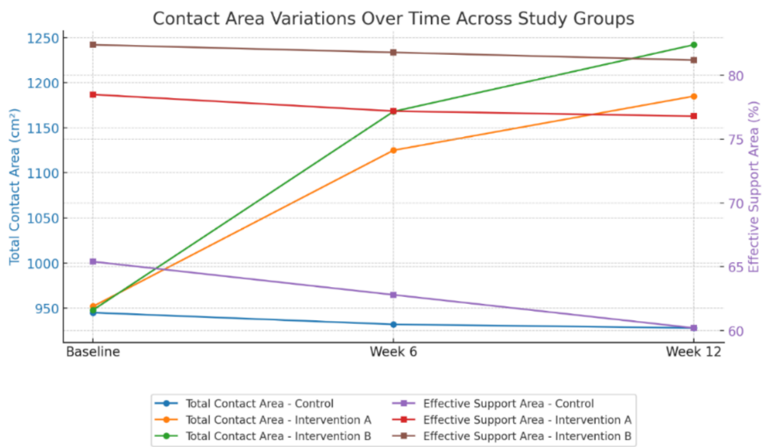

Figure 7. Contact area variations over time.

Table 13. Contact area variations over time.

Contact Parameter	**Control Group**	**Intervention A**	**Intervention B**	***p*-value**
Total Contact Area (cm^2)				
Baseline	945 ± 85	952 ± 88	948 ± 86	0.892
Week 6	932 ± 84	1125 ± 95	1168 ± 98	< 0.001*
Week 12	928 ± 83	1185 ± 98	1242 ± 102	< 0.001*
Effective Support Area (%)				
Morning	65.4 ± 5.8	78.5 ± 6.5	82.4 ± 6.8	< 0.001*
Midday	62.8 ± 5.5	77.2 ± 6.4	81.8 ± 6.7	< 0.001*
Afternoon	60.2 ± 5.2	76.8 ± 6.3	81.2 ± 6.6	< 0.001*

3.4. Group comparison outcomes

From **Figure 8**, the comparative analysis of intervention outcomes across the three study groups revealed significant differences in effectiveness and temporal adaptation patterns over the 12-week study period. All parameters showed statistically significant differences between groups (p < 0.001). As shown in **Table 14**, spinal alignment improvements were markedly different among groups. From **Figures 9** and **10**, the control group showed slight deterioration (−2.5 ± 1.2), intervention groups demonstrated substantial improvements, with Intervention Group B showing superior results (+32.6 ± 3.8) compared to Intervention Group A (+24.8 ± 3.5). Similar patterns were observed in sustained correct posture, where Intervention Group B achieved the highest improvement (+38.4 ± 4.2) compared to Intervention Group A (+28.5 ± 3.6) and the control group's decline (−3.2 ± 1.4).

Table 14. Comparative analysis of group outcomes (12-week results).

Parameter	Control Group	Intervention A	Intervention B	Between-Group *p*-Value
Spinal Alignment	−2.5 ± 1.2	+24.8 ± 3.5	+32.6 ± 3.8	< 0.001*
Sustained Correct Posture	−3.2 ± 1.4	+28.5 ± 3.6	+38.4 ± 4.2	< 0.001*
Postural Deviation Frequency	+4.8 ± 1.5	−35.6 ± 4.2	−48.2 ± 4.8	< 0.001*

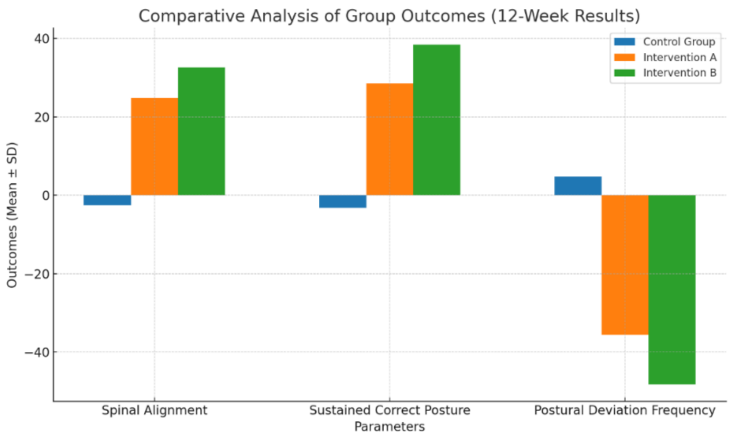

Figure 8. Comparative analysis of group outcomes.

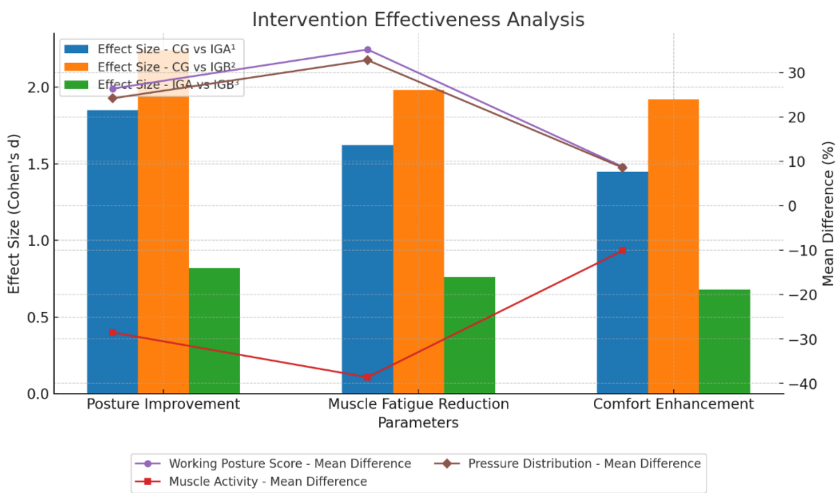

Figure 9. Intervention effectiveness analysis.

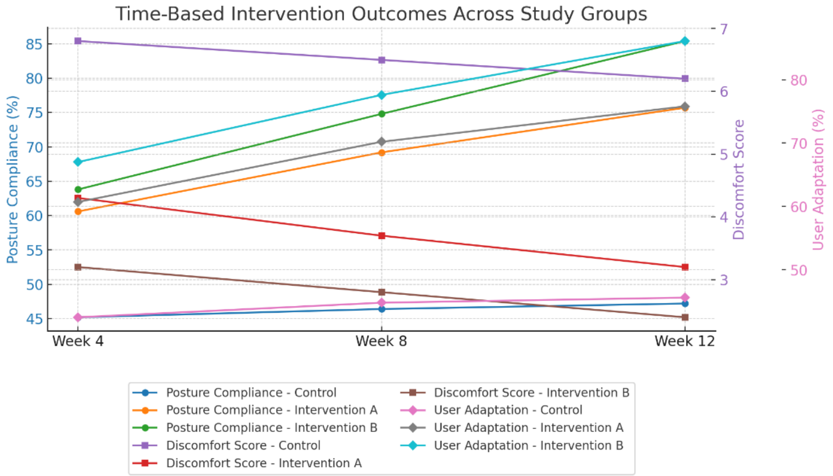

Figure 10. Time-based intervention outcomes.

The intervention effectiveness analysis presented in **Table 15** revealed substantial differences between groups, quantified through effect sizes and mean differences. The comparison between the control group and Intervention Group B showed the most significant effect sizes across all parameters (posture improvement: d = 2.24; muscle fatigue reduction: d = 1.98; comfort enhancement: d = 1.92). The mean differences in working posture score showed significant improvements in both intervention groups compared to the control group (IGA: +26.4%; IGB: +35.2%), with Intervention Group B demonstrating superior outcomes. The temporal progression analysis in **Table 16** demonstrated a clear pattern of improvement over time. By week 12, Intervention Group B achieved the highest posture compliance (85.4% ± 6.8%) compared to Intervention Group A (75.7% ± 6.2%) and the control group (47.2% ± 5.0%). Discomfort scores showed consistent improvement in both intervention groups, with Intervention Group B achieving the lowest final score (2.4 ± 0.3) compared to Intervention Group A (3.2 ± 0.4) and the control group (6.2 ± 0.7). User adaptation rates followed a similar trend, with Intervention Group B showing the highest adaptation percentage by week 12 (86.1% ± 6.9%). Notably, the incremental improvement between Intervention Groups A and B (IGA vs IGB) was smaller than the improvements between the intervention and control groups, yet still statistically significant. This suggests that while both interventions were adequate, the addition of feedback in Intervention B provided meaningful additional benefits.

Table 15. Intervention effectiveness analysis.

Parameter	**CG vs. IGA[1]**	**CG vs. IGB[2]**	**IGA vs. IGB[3]**
Effect Size (Cohen’s d)			
Posture Improvement	1.85*	2.24*	0.82*
Muscle Fatigue Reduction	1.62*	1.98*	0.76*
Comfort Enhancement	1.45*	1.92*	0.68*
Mean Difference (%)			
Working Posture Score	+26.4*	+35.2*	+8.8*
MA	−28.5*	−38.6*	−10.1*
PD	+24.2*	+32.8*	+8.6*

Table 16. Time-based intervention outcomes.

Time Point	Parameter	Control Group	Intervention A (IGA)	Intervention B (IGB)	*p*-value
Week 4	Posture Compliance (%)	45.2 ± 4.8	60.6 ± 5.2	63.8 ± 5.4	0.002*
	Discomfort Score	6.8 ± 0.8	4.3 ± 0.6	3.2 ± 0.5	< 0.001*
	User Adaptation (%)	42.5 ± 4.5	60.7 ± 5.3	67.0 ± 5.8	< 0.001*
Week 8	Posture Compliance (%)	46.4 ± 4.9	69.2 ± 5.8	74.8 ± 6.2	< 0.001*
	Discomfort Score	6.5 ± 0.7	3.7 ± 0.5	2.8 ± 0.4	< 0.001*
	User Adaptation (%)	44.8 ± 4.6	70.2 ± 6.0	77.6 ± 6.4	< 0.001*
Week 12	Posture Compliance (%)	47.2 ± 5.0	75.7 ± 6.2	85.4 ± 6.8	< 0.001*
	Discomfort Score	6.2 ± 0.7	3.2 ± 0.4	2.4 ± 0.3	< 0.001*
	User Adaptation (%)	45.6 ± 4.8	75.8 ± 6.3	86.1 ± 6.9	< 0.001*

4. Conclusion and future work

This study's comprehensive analysis of biomechanical parameters and intervention outcomes provides strong evidence for the effectiveness of integrated ergonomic approaches in improving workplace posture and comfort. Several key conclusions can be drawn from the research findings: The combination of ergonomic setup and real-time feedback (Intervention B) demonstrated superior outcomes across all measured parameters, with significant improvements in SP (+32.6 ± 3.8°), MA (37.8% reduction in trapezius activity), and PD (29.5% reduction in peak pressures). These improvements were more significant than those observed in the ergonomic setup alone group (Intervention A) and the control group. The temporal analysis revealed progressive adaptation to improved postural habits, with Intervention Group B achieving the highest compliance rate (85.4% ± 6.8%) by week 12. This suggests that real-time feedback facilitates and maintains positive postural behaviors. The sustained improvement in MA patterns and PD further supports the long-term effectiveness of the integrated intervention approach. User adaptation rates and comfort levels consistently improved throughout the study period, with Intervention Group B demonstrating the most favorable outcomes (86.1% ± 6.9% adaptation rate). This indicates that the proper ergonomic setup and continuous feedback create an optimal environment for developing and maintaining healthy sitting habits. These findings have significant implications for workplace health promotion and ergonomic intervention strategies. The study demonstrates that while beneficial, traditional ergonomic approaches can be substantially enhanced by integrating real-time feedback mechanisms. This research provides a foundation for developing more effective workplace interventions that address seated work's physical and behavioral aspects.

Future research should investigate the long-term sustainability of these improvements and explore the potential for technology-enhanced ergonomic interventions in various workplace settings. We are developing more sophisticated feedback mechanisms, and their integration into existing office furniture and equipment warrants further investigation.

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Availability of data and materials: Not applicable.

Conflict of interest: The author declares no conflict of interest.

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