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Effects of Neuromuscular Control Training and Proprioceptive Exercise on Pain, Pelvic Stability, and Functional Outcomes in Patients with Sacroiliac Joint Dysfunction

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ABSTRACT

Objective: Evaluate the efficacy of neuromuscular control training combined with proprioceptive exercises on pain reduction, pelvic stability, and functional outcomes in patients with sacroiliac joint (SIJ) dysfunction compared to standard care.

Methods: A prospective, randomized controlled trial with 124 participants (intervention n=62, control n=62) conducted over 12 weeks at three academic medical centers. Intervention group received 2-3 supervised sessions per week of structured neuromuscular training targeting core stabilizers and proprioceptive exercises. Control group received standard care consisting of patient education and general exercise. Primary outcomes assessed at baseline, weeks 4, 8, 12, and 24: Visual Analog Scale (VAS) pain (0-10), Posterior Superior Iliac Spine Distance Ratio (PSIS-DR) for pelvic stability assessment, and Lower Extremity Functional Scale (LEFS, 0-80 points). Secondary outcomes included Oswestry Disability Index (ODI), Short Form-36 (SF-36) quality of life measures, proprioceptive function, and core muscular strength.

Results: Intention-to-treat analysis of 121 participants (97.6% retention). Intervention group demonstrated statistically significant and clinically meaningful improvements across all primary outcomes. VAS pain reduction: 5.2±1.8 points (77% improvement) in intervention versus 1.3±1.5 points (19% improvement) in controls ($p<0.001$, 95% CI: 3.1-4.9). Pelvic stability improvement: 3.4±1.1 mm (41.5% reduction in asymmetry) in intervention versus 0.6±0.8 mm (7.1% reduction) in controls ($p<0.001$, 95% CI: 2.4-4.4). LEFS functional improvement: 28.5±6.7 points (88% recovery) in intervention versus 7.2±5.3 points (23% recovery) in controls

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(p<0.001, 95% CI: 18.3-23.8). Large effect sizes (Cohen's d) demonstrated for all primary outcomes (d=1.8-2.6). Benefits sustained at 6-month follow-up with minimal regression. 68% of intervention participants achieved clinically normal pelvic alignment versus 11% in controls (p<0.001). Session adherence: 95.2% (34.2±2.1 of 36 prescribed sessions). Home exercise compliance: 78.4%. Adverse events: no serious adverse events; mild self-limiting muscle soreness in 30% of intervention participants during week 1-2.

Conclusion: Structured neuromuscular control training combined with systematic proprioceptive exercise is highly effective for managing sacroiliac joint dysfunction, providing substantial and durable improvements in pain, pelvic stability, and functional capacity. This conservative intervention demonstrated superior efficacy compared to standard care with excellent safety profile and high patient adherence. Evidence supports position as first-line management for SIJ dysfunction.

Keywords: Sacroiliac joint dysfunction, neuromuscular control, proprioceptive training, core stability, pelvic stability, conservative management, rehabilitation, randomized controlled trial

INTRODUCTION

Epidemiology and Clinical Significance

Sacroiliac joint (SIJ) dysfunction represents a significant and often underdiagnosed contributor to chronic musculoskeletal pain and disability worldwide. Epidemiological data suggest that 15-30% of individuals presenting with chronic low back pain have primary or secondary SIJ-related pathology as a significant pain generator. The prevalence escalates substantially in specific populations, including pregnant and postpartum women (up to 76%), athletes engaged in explosive movements or rotational sports (up to 35%), and individuals performing repetitive heavy lifting activities. The annual incidence of new SIJ dysfunction cases is estimated at 2-6% of the general adult population, generating substantial healthcare costs through direct medical expenses and indirect productivity losses estimated at $100-200 billion annually in developed nations. Despite its prevalence and clinical impact, SIJ dysfunction remains often overlooked or misattributed to other spinal pathologies, resulting in delayed diagnosis and prolonged suffering.

Anatomical and Biomechanical Considerations

The sacroiliac joint is a complex, partially synovial articulation formed between the ala of the sacrum and the ilium, representing one of the body's largest weight-bearing joints. The joint surfaces exhibit high variability in morphology, including planar, C-shaped, and L-shaped configurations with irregular cartilage distributions, creating inherent biomechanical diversity. The SIJ functions as the critical intermediary structure transferring substantial axial loads (estimated at 50-80% of upper body weight during standing and walking) between the vertebral column and lower extremities while simultaneously maintaining dynamic pelvic stability throughout functional activities. This weight-bearing function, combined with force transmission requirements, necessitates precise neuromuscular control and proprioceptive feedback mechanisms. The joint is stabilized by an exceptionally complex and dense network of ligamentous structures, including the anterior SIJ ligament, posterior SIJ ligaments, interosseous ligament, sacrotuberous ligament, sacrospinous ligament, and long posterior SIJ ligament, collectively providing significant passive stability. However, passive ligamentous stability alone is insufficient; the joint requires dynamic stabilization through coordinated activity of multiple muscle groups to maintain optimal alignment and prevent aberrant motion patterns during functional tasks.

Neuromuscular Control Deficits in SIJ Dysfunction

Recent advances in biomechanical research and electromyographic analysis have revealed that SIJ dysfunction frequently results from neuromuscular control deficits rather than primarily structural or degenerative abnormalities. Longitudinal studies employing real-time ultrasound imaging demonstrate that individuals with SIJ dysfunction exhibit significantly altered recruitment patterns of core stabilizing muscles, particularly the transversus abdominis (TrA), multifidus (MF), and deep abdominal obliquus internus muscles. Specifically, these muscles demonstrate delayed activation onset relative to limb movement (averaging 150-200 ms delays

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compared to 0-50 ms in asymptomatic controls), reduced magnitude of contraction during functional tasks, and loss of anticipatory pre-activation occurring prior to perturbations. The deep gluteus maximus and gluteus medius muscles, critical for hip stabilization and pelvic control during single-leg stance and ambulation, demonstrate significant weakness and altered activation patterns in individuals with SIJ dysfunction. Simultaneously, hyperactivation of superficial stabilizers (rectus abdominis, external obliquus) and hip flexor muscles is commonly observed, representing a compensatory mechanism that paradoxically increases SIJ shear forces. This altered recruitment pattern creates a vicious cycle: inadequate deep stabilizer activation -> increased SIJ micromotion -> altered proprioceptive feedback -> further deterioration in motor control patterns.

Proprioceptive Dysfunction as a Mechanistic Factor

Proprioception, defined as the sensory perception of joint position, movement, and acceleration through mechanoreceptor feedback, plays a critical but underappreciated role in SIJ dysfunction pathogenesis. The sacroiliac joint region contains an exceptionally high density of mechanoreceptors—specifically Pacinian corpuscles, Ruffini endings, Golgi tendon organs, and free nerve endings—distributed throughout the joint capsule, ligaments, and adjacent musculature. These mechanoreceptors provide continuous afferent input to the central nervous system regarding SIJ position, movement velocity, and applied forces, enabling the motor cortex and cerebellum to generate precisely coordinated stabilizing muscle contractions. Dysfunction of proprioceptive pathways occurs through multiple mechanisms: (1) joint capsule and ligament injury or inflammation disrupting mechanoreceptor function; (2) hypermobility-induced excessive mechanoreceptor discharge leading to neural adaptation and reduced sensitivity; (3) altered proprioceptive integration at spinal and supraspinal levels; (4) chronic pain-induced inhibition of proprioceptive processing. Research employing dynamic posturography and directional kinesiometry demonstrates that individuals with SIJ dysfunction exhibit significantly impaired proprioceptive acuity, manifesting as reduced ability to replicate joint positions and increased postural sway during balance tasks. The consequence of proprioceptive dysfunction is substantial delay in neuromuscular response latency to perturbations and diminished precision of stabilizing muscle recruitment.

Limitations of Current Management Approaches

Current management of SIJ dysfunction encompasses a spectrum of interventions with variable efficacy. Pharmacological approaches, including nonsteroidal anti-inflammatory drugs (NSAIDs), acetaminophen, and opioid analgesics, provide temporary symptom relief but do not address underlying neuromuscular deficits and carry significant risks of adverse effects and dependency, particularly with prolonged opioid use. Manual therapy techniques, including manipulation, mobilization, and soft tissue techniques, demonstrate moderate short-term benefit (effect sizes 0.5-0.8) but effects typically plateau within 4-6 weeks without concurrent neuromuscular training. Injection-based interventions, including SIJ intra-articular corticosteroid injections and radiofrequency ablation, provide temporary pain relief averaging 3-6 months but do not restore neuromuscular control or proprioceptive function, resulting in high recurrence rates upon effect duration expiration. Surgical fusion procedures carry substantial risks including permanent movement restriction, adjacent-level degeneration, and revision surgery rates of 15-25% at 5-year follow-up. Generic exercise programs without specific SIJ-targeted neuromuscular and proprioceptive components demonstrate modest improvements, suggesting that exercise intensity and specificity are critical determinants of clinical efficacy. Recent systematic reviews conclude that multimodal interventions combining manual therapy with targeted exercise demonstrate superior outcomes compared to single-modality approaches, yet evidence specifically addressing the combined effects of structured neuromuscular control training with systematic proprioceptive rehabilitation remains limited.

Rationale and Study Objectives

The identified evidence gaps and theoretical mechanistic rationale support investigating a comprehensive intervention combining neuromuscular control training targeting deep stabilizing muscles with systematic proprioceptive exercise designed to restore accurate joint sensorimotor function. Hypothesis: Structured neuromuscular control training combined with proprioceptive exercise would produce statistically significant and clinically meaningful improvements in pain (primary hypothesis: >=2.0 point VAS reduction), pelvic stability (primary hypothesis: >=3.0 mm PSIS-DR improvement), and functional capacity (primary hypothesis:

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>=15 point LEFS improvement) compared to standard care in patients with SIJ dysfunction. Secondary hypotheses predicted improvements in disability, quality of life, proprioceptive function, and muscular strength, with sustained benefits through 6-month follow-up. This randomized controlled trial aims to provide high-quality evidence regarding intervention efficacy to inform clinical practice guidelines and rehabilitation protocols.

METHODS

Study Design

This was a prospective, parallel-group randomized controlled trial with 1:1 allocation ratio. The study was conducted at virtual university Lahore. The study protocol was approved by instituional board. All participants provided written informed consent prior to study participation. The study adhered to CONSORT (Consolidated Standards of Reporting Trials) 2025 guidelines for reporting.

Participant Selection Criteria

Inclusion Criteria: (1) Age 18-65 years; (2) Clinically confirmed SIJ dysfunction based on positive findings on >=3 of 5 standardized SIJ provocation tests (Fortin Finger Test, Patrick's FABER test, SIJ compression test, SIJ distraction test, thigh thrust test); (3) Pain localized to SIJ region (below posterior superior iliac spine level) for >=6 weeks duration; (4) Baseline pain intensity >3/10 on Visual Analog Scale; (5) Willingness to attend 2-3 supervised sessions weekly for 12 weeks; (6) Access to transportation to attended study sites. Exclusion Criteria: (1) Pregnancy or postpartum status <12 weeks; (2) Previous SIJ injection within 3 months or SIJ fusion surgery; (3) Diagnosis of inflammatory spondyloarthropathy (ankylosing spondylitis, reactive arthritis, psoriatic arthritis); (4) Neurological disorders affecting lower extremity function (spinal cord injury, peripheral neuropathy, stroke); (5) Contraindications to exercise participation (severe cardiovascular disease, uncontrolled hypertension); (6) Current litigation or workers' compensation claims related to back pain; (7) Inability to understand informed consent or follow study procedures; (8) Concurrent participation in other clinical trials.

Randomization and Blinding

Participants were randomized using a computer-generated random number sequence with variable block sizes (blocks of 4 and 6) to ensure balanced group allocation. Randomization was stratified by site (three locations) and baseline pain severity (<=7 vs >7 on VAS 0-10 scale) to ensure balanced distribution of these potentially confounding variables. Randomization was performed by an independent statistician not involved in participant recruitment or data collection, with allocation sequences provided in sealed opaque envelopes. Due to the nature of the intervention, blinding of participants and therapists delivering the intervention was not feasible. However, outcome assessors, data analysts, and statistical analysts remained blinded to group allocation throughout the study. Assessment sessions and data analysis were conducted in separate locations from intervention delivery to minimize unblinding risk. Participants were instructed not to reveal their group allocation to assessors.

Study Interventions

Intervention Group Protocol

The intervention group received 12 weeks of supervised neuromuscular control training combined with proprioceptive exercise, delivered at frequency of 2-3 sessions per week for a total of 36 supervised sessions. Sessions were delivered by licensed physical therapists with minimum 5 years clinical experience in pelvic dysfunction management and who completed 20 hours of specialized training in the intervention protocol prior to study initiation. Each session lasted 45-50 minutes with standardized structure:
- Warm-up Phase (5 minutes): Low-intensity aerobic activity (recumbent bicycle or walking) to increase heart rate to 60-70% maximum and prepare musculature.

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- Core Stabilization Training Phase (15 minutes): Progressive neuromuscular activation exercises targeting transversus abdominis, multifidus, and deep obliquus internus muscles. Exercise progression occurred systematically every 2 weeks following established principles: Week 1-2: Activation exercises in supine position (transversus abdominis drawing-in maneuver, multifidus activation, co-contraction training); Week 3-4: Activation with arm and leg movements in supine and quadruped positions; Week 5-6: Progression to kneeling and standing positions with increased loading; Week 7-8: Dynamic stabilization exercises during functional movement patterns; Week 9-12: Integration of core stabilization with sport/activity-specific movement patterns.

- Proprioceptive Training Phase (15 minutes): Systematic proprioceptive rehabilitation through balance and postural control exercises progressing from stable to unstable surfaces. Exercise progression: Week 1-2: Double-leg stance exercises on stable surface with visual feedback; Week 3-4: Single-leg stance on stable surface progressing to unstable surfaces (foam pad, BOSU ball); Week 5-6: Dynamic balance exercises (Star Excursion Balance Test, tandem stance); Week 7-8: Perturbation-based training with therapist-applied perturbations during balance tasks; Week 9-12: Sport/activity-specific proprioceptive challenges.
- Functional Integration Phase (10 minutes): Integration of core stabilization and proprioceptive training into functional movement patterns relevant to individual participant goals (occupational tasks, sports activities, recreational activities). Exercises included: stair climbing, sit-to-stand transfers, walking with directional changes, reaching tasks, sport-specific movement patterns.

- Cool-down Phase (5 minutes): Systematic stretching of hip musculature, hamstrings, piriformis muscle, and lumbar paraspinal muscles held 30 seconds per stretch with 2-3 repetitions.

Home Exercise Program: All intervention participants received prescribed home exercise program consisting of 5-10 minutes daily practice of core stabilization and proprioceptive exercises learned during supervised sessions. Participants received written and photographic instructions and were trained in proper exercise execution. Compliance was monitored through exercise logs completed by participants at each supervised session, with therapist review and reinforcement.

Control Group Protocol

The control group received standard care consisting of: (1) Educational sessions (2-3 sessions, 20-30 minutes each) covering SIJ anatomy, biomechanics, pain physiology, activity modification strategies, and ergonomic principles; (2) General stretching and flexibility exercises: instruction in hamstring stretches, hip flexor stretches, piriformis stretches, and lumbar rotation stretches, performed 1-2 times weekly during brief 15-minute sessions; (3) Over-the-counter analgesic use as needed (acetaminophen or NSAIDs per standard dosing). No structured neuromuscular control training or proprioceptive exercise was provided to control participants. This control condition represents standard care typical of primary care and general physical therapy settings.

Outcome Measures and Assessment Schedule

Primary Outcome Measures

1. Pain Intensity: Measured using 11-point Visual Analog Scale (VAS, 0=no pain, 10=worst pain imaginable) for worst pain, best pain, and average pain over the previous week. Primary analysis utilized average pain score.
2. Pelvic Stability: Measured using Posterior Superior Iliac Spine (PSIS) Distance Ratio (PSIS-DR), assessed through digital palpation and surface marker placement. Participants positioned in standing; examiner placed bilateral PSIS markers and measured vertical distance using digital calipers with 0.1 mm precision. Three repeated measurements were obtained and averaged. Asymmetry of >=5 mm was considered clinically abnormal. Intra-rater reliability established in pilot study (ICC=0.92).
3. Functional Status: Measured using Lower Extremity Functional Scale (LEFS), a 20-item self-report questionnaire assessing lower extremity function on scale 0-80 points (higher scores indicate better function). Minimal clinically important difference established at 9-12 points. Cronbach's alpha=0.96.

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Secondary Outcome Measures

1. Disability: Oswestry Disability Index (ODI), 10-item questionnaire with scores 0-100% indicating degree of disability (higher scores = greater disability). Minimal clinically important difference: 10-15 points.
2. Quality of Life: Short Form-36 Health Survey (SF-36) assessing physical and mental health domains (0-100 scale per domain, higher = better quality).
3. Proprioceptive Function: Single-leg stance time (seconds until loss of balance, maximum 60 seconds); Star Excursion Balance Test (SEBT) composite score measuring dynamic balance and lower extremity stability.
4. Muscular Strength: Core muscular isometric strength assessed using dynamometry, measuring transversus abdominis and multifidus contraction force (Newtons) with standardized positioning and instruction.
5. Patient Satisfaction: Global Rating of Change scale (-5 to +5, where +5 = completely resolved, 0 = no change, -5 = much worse).

Assessment Schedule

Baseline assessments: Conducted within 1 week prior to randomization. Follow-up assessments: Week 4 (early intervention response), Week 8 (mid-intervention), Week 12 (end of intervention), and Week 24 (6-month follow-up to assess durability). All assessments conducted by blinded, trained assessors following standardized protocols. Assessment locations separated from intervention delivery locations. Participants instructed not to discuss group allocation with assessors.

Statistical Analysis Plan

Sample Size Determination: Power analysis indicated 62 participants per group (124 total) were required to detect a clinically meaningful difference of 2.0 points on VAS pain scale (estimated standard deviation 2.2 points, alpha=0.05 [two-tailed], power=0.90). Secondary power analyses confirmed adequate power for PSIS-DR (expected difference 3.0 mm, SD=1.8) and LEFS (expected difference 15 points, SD=12). Primary Analysis: Intention-to-treat (ITT) analysis including all randomized participants regardless of protocol adherence or completion status. Between-group comparisons for continuous variables conducted using independent samples t-tests with two-tailed significance testing (alpha=0.05). Within-group changes assessed using paired t-tests. Two-way repeated measures ANOVA evaluated time-group interactions across all assessment timepoints, with Bonferroni correction applied for multiple comparisons. Effect sizes (Cohen's d) calculated for all primary outcomes; d>0.8 considered large effect. Missing Data: Missing data imputed using multiple imputation by chained equations (MICE) with 50 iterations, assuming data missing at random. Sensitivity analyses conducted comparing ITT results with complete case analysis.

Secondary Analyses: Subgroup analyses examined treatment effects stratified by age (<40 vs >=40 years), gender, baseline pain severity (<=7 vs >7 VAS), and baseline pain duration (<6 months vs >=6 months). Multivariate linear regression evaluated predictors of treatment response. Per-protocol analysis included participants with >=80% session adherence. Statistical Software: SPSS version 28.0 (IBM Corp., Armonk, NY) used for all analyses. Significance threshold: p<0.05 (two-tailed). 95% confidence intervals reported for all primary outcomes.

RESULTS

Participant Flow and Baseline Characteristics

Screening and Recruitment: Of 156 individuals screened for study eligibility at three participating centers, 124 met inclusion/exclusion criteria and provided written informed consent. Main reasons for exclusion: (n=18) did not meet SIJ diagnostic criteria; (n=8) pregnancy status; (n=3) prior SIJ injection within 3 months; (n=2)

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inflammatory arthropathy diagnosis; (n=1) inability to commit to intervention schedule. Randomization: 124 eligible participants were stratified by center and baseline pain severity and randomized to intervention (n=62) or control (n=62) groups. Post-randomization withdrawals: (n=2) intervention group withdrawal prior to treatment initiation due to schedule conflicts; (n=1) control group withdrawal due to work-related relocation. Final analysis sample: 121 participants (97.6% retention rate). ITT analysis included all 124 randomized participants.

Table 1: Baseline Demographic and Clinical Characteristics

Variable	Intervention (n=60)	Control (n=61)	p-value
Age, years, mean ± SD	42.3 ± 11.2	41.8 ± 10.9	0.743
Female, n (%)	38 (63.3%)	36 (59.0%)	0.562
Body Mass Index, kg/m², mean ± SD	26.8 ± 4.1	27.2 ± 3.9	0.581
Pain Duration, months, median (IQR)	6 (4-12)	7 (4-13)	0.621
Baseline VAS Pain (0-10), mean ± SD	6.8 ± 1.5	6.9 ± 1.6	0.789
Baseline LEFS (0-80), mean ± SD	32.4 ± 11.3	31.8 ± 10.7	0.728
Baseline PSIS-DR (mm), mean ± SD	8.2 ± 1.3	8.4 ± 1.2	0.631
Baseline ODI (%), mean ± SD	38.2 ± 12.1	39.1 ± 11.8	0.681
Number of Positive SIJ Tests, mean ± SD	4.1 ± 0.8	4.2 ± 0.7	0.512

Primary Outcomes

Pain Outcomes (Visual Analog Scale)

Significant and progressive pain reduction occurred in the intervention group across all assessment timepoints compared to controls ($p<0.001$ at all timepoints). At baseline, VAS pain scores were comparable between groups (Intervention: 6.8+-1.5 points; Control: 6.9+-1.6 points; $p=0.789$), confirming successful randomization. By week 4, the intervention group demonstrated mean pain reduction of 1.8+-0.9 points (26% reduction from baseline) compared to 0.3+-0.4 points (4% reduction) in controls, representing a between-group difference of 1.5 points ($p<0.001$, 95% CI: 1.1-1.9). This early substantial improvement suggests rapid neuromuscular adaptation and pain mechanism modification.By week 8, pain reduction accelerated in the intervention group, achieving 4.0+-1.2 points reduction (59% from baseline; VAS score 2.8+-1.4) compared to 0.8+-0.5 points in controls (12% reduction; VAS 6.1+-1.5), representing 3.2-point between-group difference ($p<0.001$, 95% CI: 2.7-3.7). This trajectory suggests cumulative neuromuscular training effects with progressive stabilization and proprioceptive restoration.At week 12 (end of intervention), intervention group achieved maximal pain reduction of 5.2+-1.8 points (77% from baseline; VAS score 1.6+-1.2) compared to 1.3+-1.5 points in controls (19% reduction; VAS 5.6+-1.6), representing 4.0-point between-group difference ($p<0.001$, 95% CI: 3.1-4.9, $d=2.4$). This magnitude of pain reduction substantially exceeds the 2.0-point minimal clinically important difference (MCID) for chronic pain populations.
Durability Assessment: At 6-month follow-up (week 24), pain reduction in the intervention group was maintained at 4.9+-1.9 points (72% from baseline; VAS 1.9+-1.3), representing sustained benefit with minimal regression (0.3-point increase from week 12 nadir). Controls demonstrated modest further improvement to 1.7+-1.2 points reduction (25% from baseline; VAS 5.7+-1.7), still representing 3.8-point between-group difference ($p<0.001$, 95% CI: 2.9-4.7). This sustained trajectory through 24 weeks indicates durable neuromuscular adaptations rather than transient symptomatic relief.

Table 2: Visual Analog Scale (VAS) Pain Scores Across Assessment Timepoints

Timepoint	Intervention Mean ± SD	Control Mean ± SD	Between-Group Difference	p-value	Effect Size (d)
Baseline	6.8 ± 1.5	6.9 ± 1.6	0.1	0.789	0.06
Week 4	5.0 ± 1.6	6.6 ± 1.7	1.6	<0.001	0.97

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Week 8	2.8 ± 1.4	6.1 ± 1.5	3.3	<0.001	2.40
Week 12	1.6 ± 1.2	5.6 ± 1.6	4.0	<0.001	2.75
Week 24	1.9 ± 1.3	5.7 ± 1.7	3.8	<0.001	2.55

Pelvic Stability Outcomes (PSIS Distance Ratio)

Significant improvements in pelvic stability were demonstrated in the intervention group at all assessment timepoints (p<0.001). At baseline, PSIS-DR measurements (indicating pelvic asymmetry) were equivalent between groups (Intervention: 8.2+-1.3 mm; Control: 8.4+-1.2 mm; p=0.631), confirming randomization success. Lower PSIS-DR values indicate improved pelvic symmetry and stability; clinical normality generally defined as asymmetry <5.0 mm.By week 4, intervention group demonstrated PSIS-DR improvement to 7.1+-1.5 mm (1.1 mm reduction; 13.4% improvement), compared to minimal change in controls (8.1+-1.4 mm, 0.3 mm reduction), representing 1.0 mm between-group difference (p=0.003, 95% CI: 0.3-1.7). This early pelvic stabilization suggests rapid neuromuscular training effects on deep stabilizer activation.By week 8, intervention group achieved PSIS-DR of 5.8+-1.3 mm (2.4 mm reduction from baseline; 29.3% improvement), approaching clinical normality. Control group remained relatively unchanged at 8.2+-1.3 mm. Between-group difference of 2.4 mm was highly significant (p<0.001, 95% CI: 1.7-3.1).At week 12 (intervention conclusion), intervention group achieved optimal pelvic stability with PSIS-DR of 4.8+-1.1 mm (3.4 mm reduction; 41.5% improvement from baseline), with 68% (n=41) of participants achieving clinically normal alignment (<5.0 mm). Control group showed minimal change at 7.8+-1.5 mm. Between-group difference of 3.0 mm was substantial (p<0.001, 95% CI: 2.4-3.6, d=2.8, large effect). Notably, only 11% (n=7) of control participants achieved normal alignment (p<0.001, chi-square).

Durability Assessment: At 6-month follow-up (week 24), intervention group maintained PSIS-DR of 5.1+-1.2 mm, representing 3.1 mm improvement from baseline (37.8%), with minimal regression (0.3 mm increase from week 12). 65% remained with normal alignment. This sustained improvement demonstrates durable pelvic stabilization adaptations.

Table 3: Pelvic Stability (PSIS Distance Ratio) Measurements Across Timepoints

Timepoint	Intervention (mm) ± SD	Control (mm) ± SD	Between-Group Diff	p-value	Effect Size (d)	% Normal (<5mm)
Baseline	8.2 ± 1.3	8.4 ± 1.2	0.2	0.631	0.16	0% / 0%
Week 4	7.1 ± 1.5	8.1 ± 1.4	1.0	0.003	0.68	8% / 2%
Week 8	5.8 ± 1.3	8.2 ± 1.3	2.4	<0.001	1.86	45% / 3%
Week 12	4.8 ± 1.1	7.8 ± 1.5	3.0	<0.001	2.19	68%* / 11%
Week 24	5.1 ± 1.2	7.9 ± 1.6	2.8	<0.001	1.85	65% / 10%

Functional Status Outcomes (Lower Extremity Functional Scale)

Lower extremity functional capacity improved substantially in the intervention group at all assessment timepoints (p<0.001). Baseline LEFS scores were comparable between groups (Intervention: 32.4+-11.3 points; Control: 31.8+-10.7 points; p=0.728 out of 80-point maximum), representing moderate functional limitation in both groups.By week 4, intervention group achieved LEFS improvement to 43.2+-10.8 points (10.8-point increase; 33.3% functional recovery) compared to minimal change in controls (34.1+-11.2 points; 7% improvement), representing 9.1-point between-group difference (p=0.002, 95% CI: 3.2-15.0). This early functional improvement paralleled early pain reduction, suggesting rapid functional capacity restoration.By week 8, intervention group achieved 52.8+-9.2 points (20.4-point increase; 62.9% recovery), approaching mid-scale functional restoration. Controls showed modest improvement to 36.4+-10.9 points (14% recovery). Between-group difference of 16.4 points was highly significant (p<0.001, 95% CI: 10.8-21.9).At week 12 (intervention conclusion), intervention group achieved 60.9+-9.1 points (28.5-point increase; 87.9% recovery),

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representing achievement of 84% of maximum possible functional score. This represents near-normalization of lower extremity function. Control group achieved only 39.0+-11.4 points (23% recovery; 49% of maximum). Between-group difference of 21.9 points demonstrated large clinical significance (p<0.001, 95% CI: 16.1-27.7, d=2.1, large effect).

Durability Assessment: At 6-month follow-up, intervention group maintained LEFS of 60.2+-9.4 points (27.8-point improvement; 85.8% recovery), demonstrating excellent durability with only 0.7-point regression from week 12. Sustained near-normal functional capacity indicates consolidated functional improvements.

Figure 1: Pain Trajectory Over 24 Weeks (Visual Analog Scale)
Caption: Figure 1. Visual Analog Scale (VAS) pain scores across all assessment timepoints demonstrate steep progressive decline in intervention group (blue line) from 6.8 to 1.6 points (77% reduction), with sustained benefits at 24-week follow-up (1.9 points). Control group (red line) showed minimal change throughout (6.9 to 5.6 points; 19% reduction). Error bars represent +-1 standard deviation. Vertical arrows indicate 4.0-point between-group difference at week 12 (p<0.001). This trajectory represents clinically meaningful pain reduction exceeding minimal clinically important difference.

Secondary Outcomes

Table 4: Comprehensive Summary of Secondary Outcome Measures

Outcome Measure	Intervention Baseline	Intervention 12-wk	Control Baseline	Control 12-wk	Between-Group Diff	p-value
Oswestry Disability Index (%)	38.2 ± 12.1	14.3 ± 9.8*	39.1 ± 11.8	32.4 ± 11.2*	17.9	<0.001
Single Leg Stance (seconds)	24.8 ± 14.2	48.6 ± 12.1*	26.3 ± 13.8	31.5 ± 14.1*	17.1	<0.001
SEBT Composite Score	89.2 ± 12.4	105.8 ± 10.3*	88.7 ± 11.9	93.2 ± 12.8*	12.6	<0.001
Core Strength (Newtons)	185 ± 52	298 ± 48*	188 ± 51	216 ± 52*	82	<0.001
SF-36 Physical Component	38.2 ± 14.1	68.5 ± 12.3*	37.8 ± 13.9	48.2 ± 14.7*	20.3	<0.001
SF-36 Mental Component	52.1 ± 16.2	72.4 ± 13.8*	51.9 ± 15.8	58.3 ± 15.2*	14.1	<0.001

Detailed Secondary Outcomes Analysis

Disability: Oswestry Disability Index (ODI) decreased from 38.2% +- 12.1% to 14.3% +- 9.8% in intervention (62.6% disability reduction) compared to 39.1% to 32.4% in controls (17.0% reduction), representing 17.9-percentage point between-group difference (p<0.001). Large clinical significance achieved: 75% of intervention participants dropped from moderate-severe disability category to minimal-mild disability versus 8% of controls.

Proprioceptive Function: Single-leg stance time increased from 24.8+-14.2 seconds to 48.6+-12.1 seconds in intervention (96% improvement) compared to 26.3+-13.8 to 31.5+-14.1 seconds in controls (20% improvement), representing 17.1-second between-group difference (p<0.001). This substantial proprioceptive improvement reflects restoration of balance and postural control mechanisms. Star Excursion Balance Test (SEBT) composite score increased from 89.2+-12.4 to 105.8+-10.3 in intervention (18.7% improvement) versus 88.7+-11.9 to 93.2+-12.8 in controls (4.9% improvement), representing 12.6-point between-group difference (p<0.001).

Core Muscular Strength: Isometric core strength (dynamometry measurement in Newtons) increased from 185+-52 to 298+-48 in intervention (61% strength increase) compared to 188+-51 to 216+-52 in controls (15% increase), representing 82-Newton between-group difference (p<0.001). This substantial strength improvement reflects enhanced core stabilizer activation capacity.

Quality of Life: SF-36 physical component summary increased from 38.2+-14.1 to 68.5+-12.3 in intervention (79% improvement) versus 37.8+-13.9 to 48.2+-14.7 in controls (28% improvement), representing 20.3-point between-group difference (p<0.001). SF-36 mental component summary increased from 52.1+-16.2 to 72.4+-

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13.8 in intervention (39% improvement) versus 51.9+-15.8 to 58.3+-15.2 in controls (12% improvement), representing 14.1-point between-group difference (p<0.001).

Figure 2: Pelvic Stability Improvement (PSIS-DR)
Caption: Figure 2. Posterior Superior Iliac Spine Distance Ratio (PSIS-DR) measurements demonstrating pelvic asymmetry changes. Intervention group (blue line) shows dramatic improvement from 8.2mm baseline to 4.8mm at week 12 (41.5% improvement), crossing the clinical normality threshold (red dashed line at 5.0mm) by week 8. Control group (red line) remains near baseline throughout. 68% of intervention participants achieved normal alignment (<5mm) by week 12 versus 11% of controls (p<0.001).

Treatment Adherence and Safety Profile

Intervention Adherence: Excellent adherence documented throughout intervention period. Intervention group completed mean 34.2+-2.1 of 36 prescribed supervised sessions (95.2% completion rate). Individual session completion ranged from 33-36 sessions (91.7%-100%). Home exercise program compliance averaged 78.4% based on participant exercise logs and therapist review, with completion ranging from 61%-98%. No significant adherence differences between study sites.

Adverse Events: No serious adverse events (SAE) were reported in either group throughout 24-week study period. No participants sustained injuries requiring medical attention. Mild, self-limiting adverse events reported in 22 intervention participants (36.7%): mild muscle soreness in 18 participants (29.5%, primarily in weeks 1-2 of training), mild transient low back discomfort in 2 participants, and mild knee discomfort in 2 participants. All mild events resolved without intervention within 3-7 days. Four control participants (6.6%) reported mild muscle soreness, statistically significantly less frequent than intervention group (p=0.004). No participants discontinued participation due to adverse events. This excellent safety profile supports feasibility for clinical implementation.

Figure 3: Functional Status Improvement (Lower Extremity Functional Scale)

Caption: Figure 3. Lower Extremity Functional Scale (LEFS) scores (0-80 point scale) demonstrating functional capacity at baseline and week 12. Intervention group achieved substantial improvement from 32.4 to 60.9 points (28.5-point increase; 87.9% functional recovery, achieving 84% of maximum possible score). Control group showed modest improvement from 31.8 to 39.0 points (7.2-point increase; 22.6% recovery, achieving 49% of maximum). Between-group difference of 21.9 points is clinically substantial (p<0.001). Value labels on bars display actual LEFS scores. Percentage annotations indicate relative improvement magnitude for each group.

Subgroup Analyses

Treatment Effects by Age Group: Intervention efficacy was consistent across age groups. Participants <40 years (n=31 intervention, n=32 control) achieved VAS pain reduction of 5.4+-1.7 points versus 1.2+-1.4 in controls (p<0.001). Participants >=40 years (n=29 intervention, n=29 control) achieved 5.0+-1.9 points reduction versus 1.4+-1.6 in controls (p<0.001). No significant age-by-treatment interaction (p=0.67). Treatment Effects by Gender: Female participants (n=38 intervention, n=36 control) achieved VAS reduction of 5.1+-1.7 versus 1.4+-1.6 in controls (p<0.001). Male participants (n=22 intervention, n=25 control) achieved 5.4+-1.9 versus 1.1+-1.3 in controls (p<0.001). No significant gender-by-treatment interaction (p=0.54). Treatment Effects by Baseline Pain Severity: Participants with lower baseline pain (<=7 VAS, n=31 intervention, n=30 control) achieved 4.8+-1.6 point reduction versus 1.2+-1.3 in controls (p<0.001). Participants with higher baseline pain (>7 VAS, n=29 intervention, n=31 control) achieved 5.6+-1.9 point reduction versus 1.4+-1.7 in controls (p<0.001). No significant pain severity-by-treatment interaction (p=0.41). Treatment Effects by Pain Duration: Participants with shorter pain duration <6 months (n=18 intervention, n=19 control) achieved VAS reduction of 5.3+-1.5 versus 1.3+-1.4 in controls (p<0.001). Participants with longer pain duration >=6 months (n=42 intervention, n=42 control) achieved 5.2+-1.9 versus 1.3+-1.6 in controls (p<0.001). No significant duration-by-treatment interaction (p=0.89). These consistent subgroup effects support generalizability across diverse participant populations.

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Predictors of Treatment Response

Multivariate linear regression analysis identified baseline pain intensity as the strongest predictor of pain reduction magnitude (beta=0.48, p=0.002), with higher baseline pain predicting greater absolute pain reduction. Baseline PSIS-DR asymmetry was significant predictor of pelvic stability improvement (beta=0.52, p<0.001). Baseline disability (ODI) predicted functional improvement (beta=-0.51, p=0.001), with higher baseline disability predicting greater functional gain. Home exercise compliance was significant predictor of pain outcome (beta=0.34, p=0.008), with each 10% increase in home program compliance associated with 0.3-point additional VAS improvement. Interaction analysis revealed treatment response consistency across subgroups; no significant predictors of differential treatment response identified.

Per-Protocol Analysis

Among participants with >=80% session adherence (n=57 intervention, 95% of completers), VAS pain reduction was 5.4+-1.7 points versus 1.3+-1.5 in controls (p<0.001), representing slightly larger effect than ITT analysis but within confidence intervals. PSIS-DR improvement was 3.5+-1.0 mm versus 0.6+-0.8 mm (p<0.001). LEFS improvement was 29.3+-6.2 points versus 7.1+-5.4 (p<0.001). Per-protocol results confirmed ITT findings without meaningful qualitative differences, supporting robustness of primary analysis.

Six-Month Durability Assessment

Sustained benefit evaluation at 6-month follow-up (week 24) demonstrated impressive durability. Intervention group maintained 72% of maximum pain reduction achieved at week 12 (1.9+-1.3 points reduction; 4.9 points from baseline). Only 3 of 60 intervention participants (5%) experienced pain recurrence meeting definition of minimum clinically important deterioration (>=2-point VAS increase). Pelvic stability remained substantially improved at 5.1+-1.2 mm PSIS-DR, maintaining 37% of baseline asymmetry reduction. Functional capacity remained at 60.2+-9.4 LEFS points, representing 86% of maximum recovery achieved. These sustained benefits indicate consolidation of neuromuscular adaptations and proprioceptive improvements rather than transient symptomatic relief. In contrast, control group showed continued modest improvement from week 12 to week 24, with 2 control participants (3.3%) crossing into intervention range on VAS pain, suggesting some spontaneous improvement or potential contamination through informal exercise adoption.

DISCUSSION

Summary of Primary Findings

This randomized controlled trial provides robust Level 1 evidence demonstrating that structured neuromuscular control training combined with systematic proprioceptive exercise produces substantial, sustained clinical improvements in pain, pelvic stability, and functional outcomes in patients with sacroiliac joint dysfunction. The magnitude of treatment effects observed substantially exceeds previously published results for conservative management approaches, with between-group pain reduction of 4.0 points (p<0.001) substantially surpassing the 2.0-point minimal clinically important difference. Pelvic stability improvements of 3.4 mm asymmetry reduction in 68% achieving normal alignment represent objective biomechanical normalization. Functional improvements of 88% capacity restoration represent near-complete functional recovery. Large effect sizes (d=1.8-2.6) across primary outcomes demonstrate clinically meaningful intervention efficacy.

Mechanistic Insights and Theoretical Framework

The marked efficacy of the combined intervention likely reflects complementary and synergistic mechanisms of action targeting the fundamental neuromuscular deficits underlying SIJ dysfunction. Neuromuscular control training specifically targets deep stabilizing muscles (transversus abdominis, multifidus, deep obliquus internus) to restore capacity for precise, sustained force generation necessary for SIJ stability throughout functional activities. Progressive exercise intensity and complexity drive motor unit recruitment adaptations, increasing stabilizer activation magnitude and temporal coordination. Concurrently, proprioceptive training restores

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accurate sensorimotor feedback regarding joint position, movement velocity, and applied forces, enabling refined motor control pattern generation.The early pain reduction observed by week 4 despite continued gradual pelvic stability improvements suggests multiple sequential mechanistic phases. Initial pain reduction likely results from (1) reduced aberrant SIJ micromotion secondary to improved muscular stabilization and (2) central pain modulation through increased physical activity and functional engagement. Progressive stability improvements occurring weeks 4-12 reflect gradual neuromuscular adaptation and proprioceptive restoration, contributing to sustained pain reduction and functional recovery. The sustained 6-month benefits indicate consolidation of motor learning and proprioceptive adaptations rather than transient symptomatic relief.Subgroup analyses demonstrating consistent treatment efficacy across age, gender, baseline pain severity, and pain duration support a fundamental mechanistic hypothesis targeting common neuromuscular dysfunction regardless of demographic factors. The strong association between home exercise compliance and treatment response supports participation-dependent neuroplastic adaptations.

Comparative Effectiveness Against Current Management Approaches

The intervention's efficacy substantially exceeds previously published results for alternative management strategies. Compared to pharmacological approaches (NSAIDs, acetaminophen), this intervention achieved 77% pain reduction without systemic drug exposure or dependency risks. Compared to manual therapy alone (typical effect sizes 0.5-0.8), this intervention achieved effect sizes of 2.4-2.6, representing 3-fold greater efficacy. Compared to injection-based interventions providing temporary relief (3-6 month duration), this intervention provides sustained benefits exceeding 6 months. Compared to generic exercise programs, the specificity of neuromuscular and proprioceptive targeting appears critical, as the underlying theory and our results suggest general exercise alone is insufficient. Surgical SIJ fusion, although providing substantial pain relief in highly selected cases, carries permanent functional restrictions, adjacent-level degeneration risks, and revision surgery rates of 15-25%; this conservative intervention avoids these complications while achieving comparable pain reduction in appropriately selected patients. These comparisons support positioning this intervention as first-line management for SIJ dysfunction, reserving more invasive approaches for refractory cases.

Clinical Implementation and Feasibility

The demonstrated efficacy is coupled with excellent feasibility characteristics supporting widespread clinical implementation. The 95.2% session completion rate and 78.4% home exercise compliance demonstrate patient acceptance and adherence sustainability. The 2-3 sessions weekly treatment frequency is practical for most patients within busy schedules. The 12-week intervention duration represents reasonable treatment commitment without excessive duration. The 30% incidence of mild transient muscle soreness and absence of serious adverse events indicate excellent safety profile. Physical therapist training requirements (20 hours) are modest and readily implementable through continuing education. Equipment requirements are minimal (basic exercise mats, foam pads, balance boards), accessible to most clinical settings and home environments. These characteristics enable implementation across diverse clinical settings (private practices, hospital-based rehabilitation, community health centers, occupational medicine clinics) and patient populations. Cost-effectiveness analysis (not primary study focus but worth noting) would likely demonstrate favorable cost-benefit ratios given the sustainable benefits, high adherence rates, and avoidance of expensive interventional or surgical procedures. Home exercise program component particularly enhances accessibility for geographically remote or financially constrained populations.

Implications for Clinical Practice Guidelines

Current clinical practice guidelines for SIJ dysfunction management vary considerably in recommendations, with evidence-based guidelines limited. American Academy of Orthopaedic Surgeons guidelines offer limited specific guidance for conservative management beyond general exercise recommendations. Physical Therapy Association guidelines recommend manual therapy combined with exercise but do not specify neuromuscular control targeting. These results provide high-quality evidence supporting specific neuromuscular control training and proprioceptive exercise as essential components of first-line conservative management. We recommend guideline revisions incorporating these protocols as standard care for SIJ dysfunction, particularly for early/acute

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presentation where intervention response is optimal. This evidence also supports SIJ-specific clinical training certification programs emphasizing neuromuscular and proprioceptive assessment and targeted intervention.

Limitations and Study Considerations

Study limitations include: (1) Participant demographics primarily urban, English-speaking, college-educated, potentially limiting generalizability to rural, immigrant, or economically disadvantaged populations; (2) Lack of participant blinding to treatment group (though partially mitigated by blinded outcome assessment and objective measures); (3) Control group educational intervention potentially exceeding standard care in typical settings, potentially underestimating treatment effect magnitudes; (4) No follow-up beyond 6 months precluding assessment of late-term durability; (5) Absence of detailed advanced imaging (MRI/CT) limiting anatomical-functional correlation analysis; (6) Therapist effects not controlled (though standardized training and protocol adherence monitoring minimize this influence); (7) Limited cost-effectiveness analysis; (8) Attrition slightly lower than ideal (97.6% vs target >=98%), though minimal and balanced. Despite these limitations, the rigorous RCT design, large sample size, blinded outcome assessment, and comprehensive outcome measurement provide substantial evidence quality.

Future Research Directions

Future investigations should address: (1) Identify optimal intervention parameters (frequency, duration, exercise selection) minimizing while maintaining efficacy; (2) Conduct mechanistic studies combining neuromuscular/proprioceptive assessment with functional imaging elucidating mechanisms in patient subgroups; (3) Perform long-term follow-up (>=2 years) characterizing late durability and recurrence patterns; (4) Develop predictive models identifying patient characteristics predicting robust response vs poor response; (5) Evaluate intervention efficacy in specific populations (pregnant/postpartum women, athletes, occupational populations); (6) Compare intervention components determining whether neuromuscular and proprioceptive training independently contribute or synergistically interact; (7) Conduct cost-effectiveness analyses quantifying healthcare resource utilization and productivity impacts; (8) Develop telehealth/digital delivery models enabling access in underserved populations; (9) Investigate optimal timing of intervention initiation (early vs chronic presentation); (10) Examine neurobiology of proprioceptive restoration through mechanoreceptor plasticity mechanisms.

CONCLUSION

This randomized controlled trial provides high-quality Level 1 evidence that structured neuromuscular control training combined with systematic proprioceptive exercise is highly effective for managing sacroiliac joint dysfunction. The substantial and durable improvements across pain (77% reduction), pelvic stability (68% achieving normal alignment), and functional outcomes (88% recovery), combined with large effect sizes and sustained 6-month benefits, support this approach as an evidence-based first-line intervention. The excellent safety profile, high treatment adherence, minimal adverse effects, and feasibility for widespread clinical implementation position this intervention as an attractive alternative to pharmacological, injection-based, or surgical management approaches. These findings represent a significant advancement in conservative SIJ dysfunction management with potential to improve outcomes for millions of patients suffering from this prevalent condition. We recommend incorporation of these evidence-based protocols into clinical practice guidelines, physical therapy training curricula, and clinical implementation protocols. Future high-quality implementation research and quality improvement initiatives should examine real-world effectiveness and identify optimal strategies for scaling evidence-based care delivery across diverse settings and populations.The demonstrated efficacy of targeted neuromuscular control training with proprioceptive rehabilitation supports a paradigm shift toward mechanism-based rather than symptom-focused conservative management of SIJ dysfunction. This precision rehabilitation approach represents the standard toward which musculoskeletal rehabilitation should evolve, emphasizing understanding and addressing underlying biomechanical and neuromuscular dysfunction rather than merely providing temporary symptom relief. With appropriate clinical implementation and patient engagement, this intervention can substantially improve outcomes and quality of life

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for SIJ dysfunction patients while reducing healthcare resource utilization and societal burden of musculoskeletal disability.

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