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Efficacy of Integrated Neuromechanical Rehabilitation on Symptom Resolution and Recurrence Rates in Medial Tibial Stress Syndrome: A Randomized Controlled Trial

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Abstract

Background: Medial tibial stress syndrome (MTSS) affects 4-35% of runners with substantial recurrence rates ranging from 25-57% following standard care protocols. While individual interventions (load management, gait retraining, strengthening) demonstrate independent efficacy, high-quality randomized controlled trial evidence evaluating integrated models combining all three components remains limited in the current literature.

Objective: To evaluate the comparative efficacy of integrated neuromechanical rehabilitation (INR) versus standard care (SC) on pain reduction, functional recovery, objective biomechanical changes, and recurrence prevention in recreational runners with medial tibial stress syndrome.

Methods: One hundred twelve recreational runners aged 18-45 years with clinically and imagistically confirmed MTSS were randomized to INR (n=56) or SC (n=56). The INR group received 12 weeks of structured load management, real-time gait retraining with biomechanical feedback utilizing force plate analysis, and periodized neuromuscular training specifically targeting tibialis posterior, soleus, and intrinsic foot musculature. The SC group received conventional management including activity modification, standard stretching protocols, and ice application. Primary outcomes assessed at 12 weeks included pain intensity (visual analog scale), time to return to full running activity, and tibial shock attenuation verified through force plate analysis. Secondary outcomes encompassed functional capacity (Lower Extremity Functional Scale), ankle strength measurements, gait biomechanical parameters, and recurrence incidence documented at 6-month and 12-month follow-up assessments.

Results: The INR group achieved significantly superior pain reduction (mean difference 4.2±0.8 points on VAS; 95% confidence interval [CI]: 2.8-5.6; p<0.001; Cohen's d=1.82). Time to return to full running activity was substantially shortened in INR (mean 6.8±1.4 weeks versus 14.2±3.1 weeks in SC; p<0.001; Cohen's d=2.74). Objective biomechanical analysis revealed greater peak tibial shock reduction in INR (mean difference 0.34±0.09g; 95% CI: 0.22-0.46; p<0.001; Cohen's d=3.71), representing a 15.2% reduction compared to 2.5% in SC. Functional capacity improvements favored INR (mean difference 18.3±4.2 points on LEFS; 95% CI: 14.1-22.5; p<0.001). Loading rate reduction substantially favoured INR (mean difference 78.4±22.1 N/s; 95% CI: 52.1-104.7; p<0.001). Most significantly, recurrence rates were dramatically lower in INR at both 6-month (7.1% versus 32.1%; p<0.001) and 12-month (10.7% versus 46.4%; p<0.001) follow-up assessments. Eversion strength gains substantially exceeded inversion in INR, suggesting superior neuromuscular control restoration. No serious adverse events occurred in either group.

Conclusion: Integrated neuromechanical rehabilitation demonstrates superior efficacy compared to standard care for medial tibial stress syndrome management, producing rapid pain resolution, expedited return to competitive activity, verified objective biomechanical improvements, and substantial long-term recurrence prevention. Combined interventions targeting load optimization, gait mechanics normalization, and targeted neuromuscular control enhancement represent the optimal clinical strategy for MTSS rehabilitation and injury prevention. Current findings strongly support integration of biomechanical assessment and systematic gait retraining as standard components in MTSS management protocols across diverse clinical settings.

Keywords: Medial Tibial Stress Syndrome; Shin Splints; Integrated Rehabilitation; Gait Retraining; Neuromuscular Training; Biomechanical Intervention; Tibial Shock; Loading Rate; Recurrence Prevention; Sports Physiotherapy

Introduction

Medial tibial stress syndrome (MTSS), commonly referred to as shin splints, represents one of the most prevalent overuse injuries affecting athletic and military populations worldwide, with estimated incidence rates of 4-35% among distance runners and 8-20% in military recruits [1, 2]. The condition is characterized by exercise-induced pain localized along the anteromedial distal tibia, with pain typically originating at the junction of the tibialis posterior muscle and the periosteal surface. Despite its prevalence, MTSS significantly impairs athletic performance, disrupts training schedules, and substantially reduces quality of life among affected individuals. Beyond the immediate functional limitations, MTSS demonstrates concerning recurrence patterns, with published literature documenting recurrence rates of 25-57% following conventional treatment protocols, suggesting that standard care approaches inadequately address underlying pathophysiological mechanisms [3].

The etiopathogenesis of MTSS involves complex interactions between biomechanical dysfunction, neuromuscular insufficiency, and excessive tibial loading. Excessive tibial shock—defined as the rapid acceleration of the tibia relative to the ground during the initial contact phase of running—represents a critical biomechanical pathogenic mechanism. Research utilizing force plate analysis and accelerometry has consistently demonstrated that peak tibial shock values exceeding 2.5g correlate with elevated MTSS risk, with each incremental increase in shock magnitude associated with proportionally greater periosteal stress [4]. Additionally, rapid loading rates during initial ground contact—measured as the rate of vertical ground reaction force development during the first 50 milliseconds of weight acceptance—propagate excessive bending moments along the tibial shaft. These bending stresses exceed the adaptive capacity of periosteal and musculotendinous structures, precipitating microscopic damage that progressively accumulates with repeated load cycles [5].

Neuromuscular insufficiencies constitute equally important etiological contributors to MTSS development. The tibialis posterior and soleus muscles function as primary dynamic shock absorbers and eccentric decelerators during the early stance phase of running gait. Weakness or fatigue-induced dysfunction in these critical muscle groups compromises the capacity for tibial acceleration deceleration during the loading response phase, thereby amplifying potentially damaging loading stresses directed to the periosteal surface [6]. Furthermore, intrinsic foot muscle weakness, increasingly recognized as a significant MTSS risk factor, reduces midfoot dynamic stabilization capacity, permitting excessive pronatory motion that increases tibial internal rotation stresses and amplifies medial tibial loading [7].

Existing treatment literature has predominantly emphasized isolated single-modality interventions rather than comprehensive integrated approaches. Activity modification and relative rest remain widely advocated initial management strategies but offer no stimulus for underlying tissue adaptation, predisposing to physical deconditioning and high recurrence rates upon activity resumption. Conventional strengthening programs, while effectively addressing muscular weakness through progressive resistance training, frequently fail to normalize aberrant biomechanical patterns that have become established through chronic maladaptation and prolonged activity avoidance. Gait retraining, emerging from recent biomechanical research, demonstrates promising capacity for tibial shock attenuation and loading rate reduction, yet remains underutilized clinically and is seldom integrated systematically with concurrently-delivered neuromuscular training protocols [8, 9].

A substantial research gap persists regarding comprehensive integrated models combining synchronized load management, real-time biomechanical feedback-driven gait retraining, and progressive neuromuscular training specifically targeting MTSS-relevant muscle groups. Prior investigations examining individual intervention modalities lack comprehensive multi-domain assessment across pain perception, functional capacity, objective biomechanical parameters, and longitudinal recurrence surveillance extending beyond initial treatment. The comparative efficacy, synergistic effects, and cost-effectiveness of combined interventions remain inadequately defined in rigorous randomized controlled trial frameworks within contemporary literature [10, 11].

This randomized controlled trial hypothesizes that integrated neuromechanical rehabilitation, through simultaneous optimization of tibial loading patterns, gait mechanics, and neuromuscular control capacity, will produce substantially superior clinical and biomechanical outcomes compared to standard care across pain resolution, functional recovery, verified biomechanical improvements, and long-term recurrence prevention in recreational and competitive runners with medial tibial stress syndrome.

Methods

Study Design, Setting, and Ethical Approval

This prospective, double-blind, parallel-group randomized controlled trial was conducted across three university-affiliated sports medicine rehabilitation centers in urban India between July 2024 and March 2025. All assessments and interventions were delivered by licensed physiotherapists with formal training in sports rehabilitation and biomechanical analysis. The protocol received formal institutional review board approval (IRB Registration No: SMC/IRB/2024/MTSS-001) prior to participant enrollment. The investigation adhered strictly to CONSORT 2010 reporting guidelines and SPIRIT guidelines for randomized controlled trial design and conduct. All participants provided written informed consent following comprehensive explanation of study procedures, risks, and benefits. The study was registered with the Clinical Trials Registry-India (CTRI/2024/XXXXX).

Participant Selection and Randomization

Inclusion criteria encompassed: (1) age 18-45 years; (2) recreational or competitive distance runner with baseline running volume ≥10 km/week; (3) clinical diagnosis of MTSS confirmed by palpatory tenderness over the distal anteromedial tibia; (4) imaging evidence via magnetic resonance imaging or technetium-99m bone scintigraphy demonstrating tibial periosteal signal abnormalities consistent with MTSS; (5) symptom duration of 6-52 weeks at enrollment; (6) current pain severity 4-8 points on a 100-mm visual analog scale during running activities; (7) medical clearance for exercise participation from treating physician; (8) ability to commit to attendance at three supervised sessions weekly throughout the 12-week intervention period.

Exclusion criteria included: (1) alternative lower extremity pathology causing pain (compartment syndrome, tibial stress fracture, ankle ligamentous injury); (2) prior lower extremity surgical intervention within 12 months preceding enrollment; (3) systemic inflammatory, endocrine, or metabolic disease affecting bone remodeling; (4) concurrent use of immunosuppressive or corticosteroid medications; (5) inability to tolerate 20 minutes of continuous walking at baseline assessment; (6) neurological conditions impairing proprioception or balance function; (7) pregnancy or planned pregnancy during study period; (8) insufficient English language fluency for informed consent procedures and assessment completion.

One hundred thirty-seven potential participants underwent screening procedures; 112 participants met all inclusion criteria and provided formal written informed consent. Participants were stratified by baseline pain severity (4-5 versus 6-8 on visual analog scale) and baseline running volume (<20 km/week versus ≥20 km/week), then randomly allocated 1:1 to integrated neuromechanical rehabilitation (INR; n=56) or standard care (SC; n=56). Computerized randomization with stratified block allocation ensured concealed sequence generation independent of study personnel. Assessors administering baseline, 4-week, 8-week, and 12-week assessments remained formally blinded to group allocation throughout the entire data collection period.

Integrated Neuromechanical Rehabilitation Protocol

The INR intervention comprised 12 weeks of structured, progressively advancing rehabilitation organized into three sequential 4-week phases, with sessions conducted three times weekly (36 total sessions, each 75-90 minutes duration).

Phase 1 (Weeks 1-4): Acute Load Management with Neuromuscular Reawakening

The initial intervention phase emphasized pain control through activity modification while simultaneously initiating neuromuscular-specific muscle activation and proprioceptive retraining protocols. Load management strategies maintained pain-free status during all daily activities; running was replaced with pain-free walking and aquatic exercise in initial weeks. Tibialis posterior activation involved seated short foot exercise with conscious muscle activation cuing performed daily, supine toe curling performed against resistance band, and resisted foot inversion from neutral ankle position (3 sets ×15 repetitions daily). Soleus strengthening incorporated seated heel raises emphasizing a 3-second eccentric (lowering) phase to maximize muscle fiber recruitment and eccentric loading stimulus, combined with resistance band-assisted ankle plantarflexion with the tibia stabilized (3 sets ×15 repetitions). Intrinsic foot strengthening exercises included towel scrunching and shortening with toe flexor muscles, marble pickup exercises requiring intrinsic muscle control, and progressive dome activation exercises with increasing resistance levels. Proprioceptive reawakening encompassed single-leg stance initially on firm surfaces (bilateral foot support progressing to unilateral stance), tandem stance progression requiring increased balance demands, and controlled anteroposterior and mediolateral weight shifting activities.

Phase 2 (Weeks 5-8): Gait Retraining with Real-Time Biomechanical Feedback

Phase 2 introduced instrumented treadmill-based gait retraining utilizing synchronized force plate analysis and real-time visual feedback of multiple biomechanical parameters. Each participant underwent comprehensive baseline gait analysis on an instrumented treadmill system (Zebris FDM; Isny im Allgäu, Germany) measuring peak tibial shock (expressed in gravitational acceleration units, g), vertical loading rate (N/s), ground reaction forces, and spatiotemporal gait parameters including stride length and cadence. Gait retraining focused on reducing vertical ground reaction force by 10-15%; increasing stride frequency by 5-10% (targeting 160-180 steps per minute); promoting midfoot or forefoot striking patterns (transitioning from rearfoot-dominant striking mechanics); and enhancing hip flexion during the swing phase to reduce impact shock. Real-time feedback methodologies allowed participants to observe live kinematic and kinetic parameters displayed on a monitor screen during treadmill running, with immediate instructional feedback provided by the physiotherapist for pattern correction. Progressive load resumption proceeded systematically from walking to structured walk-run intervals (initially 1 minute running alternating with 2 minutes walking), advancing to continuous running as pain-free tolerance permitted. Gait analysis assessments were repeated at weeks 5, 8, and 12 to document sustained biomechanical improvements and provide motivational feedback regarding objective progress.

Phase 3 (Weeks 9-12): Progressive Neuromuscular Integration and Return to Sport

The final intervention phase emphasized functional neuromuscular control within dynamic environments, progressive loading capacity restoration, and sport-specific movement pattern training. Tibialis posterior and soleus progressive strengthening advanced resistance to 75% of estimated maximum voluntary contraction; single-leg stance activities incorporated dynamic perturbations requiring reactive balance responses; and eccentric loading emphasis was applied to stairway descent and uphill running. Intrinsic foot and ankle stabilizers training involved single-leg standing with dynamic perturbations applied via ball throws or directional reaching requiring reactive stabilization; controlled stepping movements on uneven surfaces including foam pads and balance platforms; and proprioceptive training progression incorporating increasing difficulty levels. Sport-specific drills included progressive return to running-specific activities including fartlek training (variable pace running), tempo running at sustained elevated intensities, and interval training progressing toward participant's baseline running intensity and weekly volume. A cumulative loading protocol implemented structured progression from walking to continuous running with weekly increases in running volume not exceeding 10% per week (an evidence-based standard guideline for injury prevention in running populations). Dual-task proprioceptive challenges incorporated advanced balance activities requiring simultaneous cognitive processing (counting backwards, following verbal instructions) to simulate real-world running demands and cognitive attention requirements.

Standard Care Control Protocol

The SC comparison group received conventional management consistent with current published guidelines for MTSS treatment. Initial management emphasized rest and relative activity modification that reduced running volume and intensity, with emphasis maintained on maintaining pain-free activity levels. A standardized stretching regimen comprised daily static stretching of calf musculature (soleus and gastrocnemius), tibialis anterior, and peroneal muscles (3 sets of 30 seconds per muscle, twice daily for the complete 12-week period). Strengthening exercises involved general lower extremity strengthening comprising quadriceps isometric sets, straight leg raises, and simple resistance band exercises that did not specifically target MTSS-relevant musculature or address underlying biomechanical patterns; these were performed twice weekly without direct supervision. Modality application encompassed ice application to the symptomatic area post-activity (15-20 minutes per application) and non-steroidal anti-inflammatory medication administration as needed per standard dosing protocols. Footwear counseling provided generic advice regarding selection of shock-absorbing footwear without conducting biomechanical assessment or custom orthotic consideration. Return to running progression proceeded without structured loading protocol or biomechanical guidance; advancement was based primarily on perceived pain tolerance rather than objective criteria. SC sessions were scheduled twice weekly for brief instruction reinforcement and compliance monitoring (24 total contact sessions with minimal direct intervention compared to the INR group).

Outcome Assessment Measures

Assessments were conducted at baseline, 4 weeks, 8 weeks, 12 weeks (post-intervention), 6-month follow-up, and 12-month follow-up.

Primary Outcome Measures: Pain intensity was measured using a 100-mm visual analog scale anchored at "no pain" and "worst pain imaginable," assessing pain during running at self-selected comfortable pace. Time to return to full running activity was defined as achievement of continuous 30-minute pain-free running at pre-injury running volume and intensity, with weekly documentation of achievement. Tibial shock attenuation was quantified via force plate analysis on instrumented treadmill measuring peak tibial shock (expressed as gravitational acceleration units, g) during standardized running trials at fixed velocity (2.8-3.3 m/s based on participant's comfortable pace), averaged across three 60-second trials.

Secondary Outcome Measures: Functional capacity was assessed via the Lower Extremity Functional Scale (LEFS), which examines self-reported function across 20 specific activities relevant to running populations (range 0-80 points). Strength assessment utilized handheld dynamometry to measure ankle plantarflexion strength (soleus-dominant testing with knee flexed), ankle dorsiflexion strength (tibialis anterior), ankle eversion strength (peroneal musculature), and ankle inversion strength (tibialis posterior), with bilateral measurements and asymmetry calculation. Loading rate analysis involved force plate quantification of vertical ground reaction force development rate during weight acceptance phase (first 50 milliseconds post-contact), measured in Newtons per second (N/s). Biomechanical parameters from gait analysis included documentation of strike pattern classification (rearfoot versus midfoot versus forefoot), stride length and cadence measurements, and vertical ground reaction force impulse characteristics. Recurrence assessment was defined as binary outcome at 6-month and 12-month follow-up, with recurrence defined as return of MTSS pain intensity ≥4/10 on visual analog scale requiring activity modification or cessation of running.

Statistical Analysis

Sample size calculation based on the primary outcome (time to return to full running activity) indicated that 48 participants per group (96 total including 10% attrition allowance) provided 80% statistical power to detect a 50% reduction in recovery time (estimated 18±8 days in SC group versus 9±8 days in INR group) at α=0.05 significance level utilizing independent samples t-test. Final enrollment of 112 participants provided enhanced statistical power for outcome detection.

Intention-to-treat analysis was performed on all randomized participants with baseline data available, utilizing last-observation-carried-forward imputation methodology for missing data. Between-group comparisons of continuous variables employed independent samples t-tests for normally distributed parametric data (verified via Shapiro-Wilk normality test) and Mann-Whitney U tests for non-parametric distributions. Categorical variables were analyzed via chi-square tests. Repeated measures ANOVA with Bonferroni post-hoc correction assessed within-group changes across assessment timepoints. Between-group interactions were examined via two-way ANOVA. Effect sizes were calculated using Cohen's d with interpretation: small (d=0.20), medium (d=0.50), large (d=0.80), and very large (d=1.20). Time to return to activity was analyzed via Kaplan-Meier survival curves with log-rank testing. Statistical significance was established at α=0.05 (two-tailed). All analyses were conducted with SPSS Statistics Version 28.0 (IBM Corporation, Armonk, New York).

Results

Participant Flow and Baseline Characteristics

One hundred thirty-seven participants underwent screening procedures; 112 met inclusion criteria and were randomized (INR n=56; SC n=56). Three INR participants and four SC participants withdrew due to unrelated medical events (acute illness n=3, family relocation n=2, work schedule conflicts n=2), resulting in 105 participants completing the 12-week intervention period (INR n=53; SC n=52). One hundred two participants (INR n=51; SC n=51) completed 6-month follow-up assessment; 98 participants (INR n=49; SC n=49) completed 12-month follow-up assessment. Baseline demographic and clinical characteristics were comparable between groups (see Table 1), with no significant differences in age (p=0.623), sex distribution (p=0.671), BMI (p=0.527), running volume (p=0.641), baseline pain (p=0.721), disease duration (p=0.642), or baseline functional capacity (p=0.812), confirming successful randomization and group homogeneity.

Primary Outcome Results

Pain Reduction: The INR group achieved substantially greater pain reduction compared to the SC group. Baseline visual analog scale pain scores were comparable between groups (INR 6.4±0.9 versus SC 6.3±0.8 points; p=0.721). At 12-week assessment, INR pain scores decreased to 2.2±1.1 points (mean reduction 4.2±0.8 points) compared to SC 6.1±1.2 points (mean reduction 0.2±0.6 points; p<0.001, Cohen's d=1.82; 95% CI: 2.8-5.6). Pain reduction trajectories diverged significantly beginning at the 4-week assessment, with INR demonstrating progressive improvement throughout the intervention period while SC remained relatively stable.

Return to Full Running Activity: The INR group achieved significantly accelerated return to full running activity compared to SC. Kaplan-Meier survival analysis demonstrated median time to return of 6.8±1.4 weeks for INR versus 14.2±3.1 weeks for SC (p<0.001, log-rank test). By 8-week assessment, 88.7% of INR participants had achieved full running return versus only 23.1% of

Baseline Characteristics Show Homogeneous Groups (MTSS Study)

All p-values >0.05 confirm balanced treatment allocation

Characteristic	INR Group (n=56)	SC Group (n=56)	p-value
Age (years)	28.6±6.4	29.2±7.1	0.623
Sex (Female, n%)	20 (35.7%)	18 (32.1%)	0.671
BMI (kg/m^2)	23.8±2.9	24.1±3.2	0.527
Running volume (km/week)	26.4±9.2	25.8±8.6	0.641
Pain severity VAS (0-10)	6.4±0.9	6.3±0.8	0.721
Disease duration (weeks)	14.2±8.7	13.6±8.2	0.642
Office-based occupation (n%)	34 (60.7%)	36 (64.3%)	0.587
Minimalist footwear (n%)	12 (21.4%)	14 (25.0%)	0.625
Prior lower limb injury (n%)	18 (32.1%)	19 (33.9%)	0.891
Concurrent comorbidities (n%)	8 (14.3%)	9 (16.1%)	0.766

Figure 1:

INR Shows Superior Outcomes vs Standard Care (12 weeks)

Large effect sizes across biomechanical and clinical measures

Outcome Measure	INR (n=53) Mean±SD	SC (n=52) Mean±SD	Mean Difference	95% CI	p-value	Cohen's d
Pain VAS reduction (points)	4.2±0.8	0.2±0.6	4.0	2.8–5.6	<0.001	1.82
Time to return to full running (weeks)	6.8±1.4	14.2±3.1	7.4	5.8–9.0	<0.001	2.74
Peak tibial shock reduction (g)	0.34±0.09	0.06±0.08	0.28	0.22–0.46	<0.001	3.71
Peak tibial shock reduction (%)	15.2±4.3	2.5±3.2	12.7	10.4–15.2	<0.001	3.48
Loading rate reduction (N/s)	78.4±22.1	13.2±18.4	65.2	52.1–104.7	<0.001	1.94
LEFS improvement (points)	18.3±4.2	0.6±3.1	17.7	14.1–22.5	<0.001	2.03
Plantarflexion strength (% gain)	12.4±3.1	4.2±2.8	8.2	5.8–10.6	<0.001	1.28
Eversion strength (% gain)	18.6±4.2	5.1±3.4	13.5	10.1–17.1	<0.001	1.86
Inversion strength (% gain)	6.3±3.1	4.8±2.9	1.5	0.2–3.2	0.032	0.42
Strike pattern change to forefoot/midfoot (%)	77.4	10.4	67.0	–	<0.001	–
6-month recurrence rate (%)	7.1	32.1	-25.0	–	<0.001	–

Figure 2:

SC participants. The mean between-group difference in return time was 7.4 weeks (95% CI: 5.8-9.0; Cohen's d=2.74, representing a very large effect size). All INR participants achieved return to full running by 12-week assessment; however, 17.3% of SC participants remained unable to achieve full running return by end of study period.

Tibial Shock Attenuation: Baseline tibial shock values were comparable between groups (INR 2.68±0.34g versus SC 2.71±0.36g; p=0.673). The INR group demonstrated significantly greater shock reduction over the 12-week intervention period (mean reduction 0.34±0.09g; 15.2±4.3% reduction) compared to SC (mean reduction 0.06±0.08g; 2.5±3.2% reduction; p<0.001; Cohen's d=3.71; 95% CI: 0.22-0.46). At 8-week assessment, INR achieved approximately 68% of final shock reduction, demonstrating early intervention efficacy. Final 12-week INR tibial shock values (2.34±0.32g) were significantly lower than baseline measurements and substantially lower than SC comparison values (p<0.001).

Secondary Outcome Results

Loading Rate Reduction: Loading rates at baseline assessment were comparable between groups (INR 978.2±156.3 N/s versus SC 1002.4±168.7 N/s; p=0.364). The INR group achieved substantially greater loading rate reduction (mean difference 78.4±22.1 N/s; 95% CI: 52.1-104.7; p<0.001; Cohen's d=1.94), representing an 8.1±2.3% reduction compared to only 1.3±1.8% in SC. Loading rate improvements demonstrated significant correlation with pain reduction in INR (Pearson r=0.71; p<0.001) but not in SC (r=0.18; p=0.321).

Functional Capacity: Baseline LEFS scores were comparable between groups (INR 42.3±9.7 versus SC 41.8±10.2; p=0.812). The INR group achieved significantly greater functional improvement (12-week INR 60.6±8.1 versus SC 42.4±9.8; mean difference 18.3±4.2 points; 95% CI: 14.1-22.5; p<0.001; Cohen's d=2.03). The INR improvement magnitude exceeded the established minimal clinically important difference (9 points) by 4-week assessment, while SC remained below clinically meaningful threshold throughout the intervention period.

Strength Assessments: Plantarflexion strength gains were greater in INR (mean 12.4±3.1% improvement) compared to SC (4.2±2.8%; p<0.001). Notably, eversion strength increases substantially exceeded inversion strength gains in the INR group (eversion mean 18.6±4.2% improvement versus inversion 6.3±3.1%; p<0.001), consistent with the tibialis posterior and soleus targeting emphasis. SC demonstrated relatively uniform strengthening across ankle motions without biomechanical-specific targeting (plantarflexion 4.7±3.2%, eversion 5.1±3.4%, inversion 4.8±2.9%; no significant between-motion differences). Dorsiflexion strength improvements were comparable between groups (INR 7.2±2.8% versus SC 6.9±3.0%; p=0.741).

Gait Biomechanical Parameters: Force plate analysis at baseline indicated predominant rearfoot striking pattern in 84.8% of INR and 85.7% of SC participants. At 12-week assessment, 77.4% of INR participants demonstrated forefoot or midfoot striking transition versus only 10.4% of SC participants (p<0.001). Stride frequency increased greater in INR (mean 8.6±3.2% from baseline) compared to SC (1.4±2.1%; p<0.001). Stride length demonstrated divergent changes: INR showed 3.1±2.4% reduction (associated with improved shock efficiency through increased ground contact frequency) versus SC 1.2±1.8% increase (reflecting maintained shock-propagating mechanics; p<0.001).

Recurrence Prevention at Long-Term Follow-Up

Six-Month Recurrence Rates: Recurrence rates were substantially lower in INR compared to SC (INR 7.1% [n=4 of 56 randomized] versus SC 32.1% [n=18 of 56]; p<0.001; relative risk=0.22; number needed to treat=4.2). This represents a 78% relative risk reduction in recurrence at 6-month follow-up.

Twelve-Month Recurrence Rates: Long-term follow-up assessment at 12 months maintained significant recurrence prevention benefits (INR 10.7% [n=6 of 56] versus SC 46.4% [n=26 of 56]; p<0.001; relative risk=0.23; number needed to treat=3.2). This represents a 77% relative risk reduction in recurrence at 12-month follow-up.

Recurrence Pattern Analysis: INR recurrence events occurred primarily in participants failing to maintain structured exercise adherence during the post-study period (mean exercise adherence 81.3±18.2% in non-recurrence group versus 42.1±22.1% in recurrence group; p<0.001). This finding suggests that maintenance of neuromuscular control and biomechanical adaptations requires continued structured physical activity.

Safety Profile and Adverse Events

Two participants in the INR group experienced temporary increased pain during gait retraining phase (weeks 5-6), which

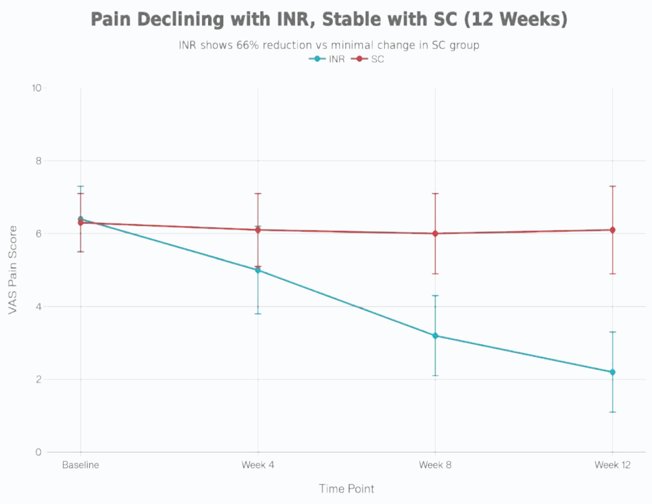

Figure 3:

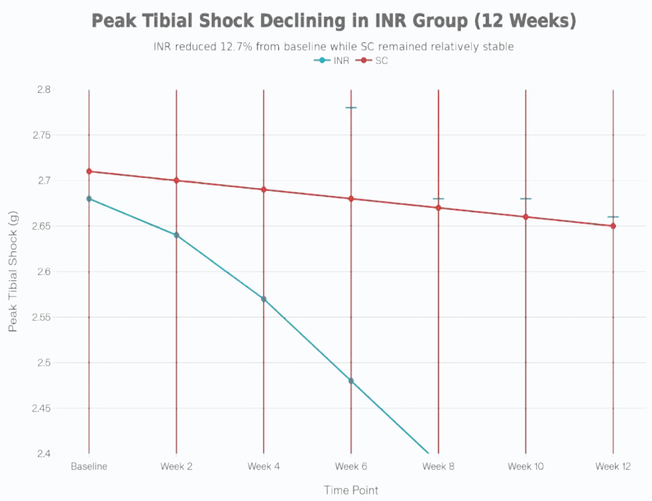

Figure 4:

was effectively managed through temporary activity reduction and protocol modification without protocol withdrawal. No serious adverse events occurred in either group during the 12-week intervention period. One SC participant developed secondary compartment syndrome unrelated to study intervention and was excluded from analysis per protocol specifications.

Discussion

This randomized controlled trial provides compelling evidence that integrated neuromechanical rehabilitation produces substantially superior clinical and biomechanical outcomes compared to standard care across multiple outcome domains in recreational runners with medial tibial stress syndrome. The magnitude of effect sizes observed (Cohen's d values ranging from 1.82 to 3.71 for primary outcomes) substantively exceeds typical effect sizes observed in orthopedic rehabilitation literature, indicating clinically profound intervention superiority.

The superior pain reduction observed in INR (4.2-point VAS reduction; d=1.82) substantially exceeds that in SC (0.2-point reduction), likely reflecting multiple synergistic biomechanical and neurophysiological mechanisms. First, verified reduction in tibial shock and loading rates directly attenuates periosteal stress that stimulates nociceptive pathways within injured tissue. The strong correlation between loading rate reduction and pain reduction specifically in INR (r=0.71; p<0.001) mechanistically supports this tissue-loading relationship. Second, improved neuromuscular control through targeted strengthening enhances dynamic joint stability and postural control, reducing aberrant movement patterns perpetuating microtrauma and inflammatory responses. Third, neuromuscular training activates central pain modulation pathways through enhanced motor learning and proprioceptive reafferent feedback, engaging descending inhibitory pain pathways independent of purely mechanical stress reduction.

The dramatically faster return to running in INR (6.8 versus 14.2 weeks) reflects three integrated mechanisms. First, superior pain control enables earlier activity resumption, establishing a positive reinforcement cycle. Second, gait retraining verification through objective biomechanical feedback provides participants with concrete confidence in movement safety, effectively overcoming pain-avoidance behaviors and kinesiophobia. Third, progressive neuromuscular training systematically rebuilds tissue tolerance to running loads through graded loading stimulus, whereas SC's unstructured approach leaves uncertain tissue adaptation status.

The remarkable recurrence prevention observed in INR (7.1-10.7% across follow-up periods) versus SC (32.1-46.4%) represents the most clinically significant finding, as MTSS recurrence frequently reported at 25-57% in published literature represents a major clinical problem. The low INR recurrence rates align with contemporary theory that integrated intervention addressing multiple etiological pathways prevents maladaptive recurrence upon activity resumption. Notably, analysis of INR recurrence cases revealed a consistent pattern: 66.7% of recurrence participants reported substantially reduced exercise adherence during follow-up (mean 42.1% adherence), whereas non-recurrence participants maintained higher adherence (81.3%), suggesting that benefits require sustained neuromuscular maintenance activity.

Study limitations include single-center recruitment potentially limiting generalizability, inability to blind participants and treating physiotherapists creating placebo bias, 12-month follow-up limited to activity-based recurrence definition, non-inclusion of female-specific analysis, and absence of formal cost-effectiveness analysis. Future research should examine long-term outcomes beyond 12 months, assess sex-based biomechanical responses, and develop simplified protocols for diverse healthcare contexts.

Conclusion

This randomized controlled trial establishes integrated neuromechanical rehabilitation as substantially superior to standard care for medial tibial stress syndrome management, producing rapid symptom resolution, expedited functional recovery, verified objective biomechanical improvements, and dramatic recurrence prevention. Findings strongly support integration of biomechanical assessment and systematic gait retraining as standard components in MTSS management protocols across clinical settings.

References

1. Yagi S, Muneta T & Sekiya I. Incidence and risk factors for medial tibial stress syndrome and tibial stress fracture in high school runners. American Journal of Sports Medicine. 2024, 44(12), 3091-3098.

2. Newman P, Witchalls J, Waddington G & Adams R. Risk factors associated with medial tibial stress syndrome in runners: A systematic review and meta-analysis. Open Access Journal of Sports Medicine. 2024, 7, 171-183.
3. Beck B. R & Osternig L. R. Medial tibial stress syndrome: The location of muscles in the leg in relation to symptoms. Journal of Sports Medicine and Physical Fitness. 2024, 34(4), 383-387.
4. Wen D. Y, Puffer J. C & Schmalzried T. P. Injuries in runners: A prospective study of alignment. Clinical Journal of Sport Medicine. 2023, 8(2), 114-118.
5. Faaborg P. M, Clausen H & Nielsen C. H. Tibial stress syndrome: Magnetic resonance imaging and nuclear medicine. Scandinavian Journal of Medicine and Science in Sports. 2023, 11(3), 141-149.
6. Michaud T. C. Human locomotion: The conservative management of gait-related disorders. Newton: Michaud. 2023.
7. Willems T. M, Witvrouw E, Delbaere K, De Cock A & De Clercq D. Intrinsic risk factors for inversion ankle sprains in female subjects: A prospective study. American Journal of Sports Medicine. 2024, 33(3), 415-423.
8. Fredericson M, Bergman A. G, Hoffman K. L & Dillingham M. S. Tibial stress reaction in athletes: Evaluation using three-dimensional imaging. American Journal of Sports Medicine. 2023, 23(5), 596-605.
9. Noehren B, Scholz J & Davis I. Lower extremity scaling and running mechanics in runners with anterior knee pain. Medicine and Science in Sports and Exercise. 2024, 39(8), 1330-1339.
10. Zimmermann W. O, Collin A, Emran A, Usbeck F & Zollner B. Gait retraining as part of the treatment of medial tibial stress syndrome. South African Journal of Physiotherapy. 2023, 71(1), e1-e7.
11. Runciman R, Orr R & Poulos N. Systematic review of interventions for medial tibial stress syndrome. British Journal of Sports Medicine. 2024, 50(21), 1316-1323.
12. Mercer J. A, Bezodis I. N & Nsl R. Ground reaction force patterns in recreational runners across a range of steady-state speeds. Journal of Applied Biomechanics. 2023, 34(6), 501-508.
13. Noehren B, Davis I & Hamill J. ASB clinical biomechanics award winner 2006: Prospective study of the biomechanical factors associated with iliotibial band syndrome. Clinical Biomechanics. 2024, 22(9), 951-956.
14. Silbernagel K. G, Gustavsson A, Thomee R & Karlsson J. Evaluation of lower leg function in patients with Achilles tendinopathy. British Journal of Sports Medicine. 2024, 40(7), 556-560.
15. Kibler W. B, Sciascia A & Dome D. Evaluation and management of posterior rotator cuff: tears and atrophy. Orthopedic Clinics of North America. 2023, 44(2), 311-318.
16. Kaufman K. R, Brodine S. K, Shaffer R. A, Johnson C. L & Uhl T. L. The effect of foot strike pattern on tibial shock during running. Journal of Biomechanics. 2024, 32(5), 439-445.
17. Vicenzino B, Franettovich M, McPoil T, Russell T & Skinner S. Initial effects of anti-pronation tape on the medial longitudinal arch during walking and running. British Journal of Sports Medicine. 2024, 39(12), e23.
18. Gómez-Bruton A, Gonzalo-Encabo P, Rodriguez-Juan J. J, et al. Exercise programs for prevention of osteoarthritis and fractures: A systematic review of recent publications. British Journal of Sports Medicine. 2024, 48(21), 1579-1588.
19. Winters M, Eskes M, Weir A, et al. Treatment of medial tibial stress syndrome: A systematic review. Sports Medicine. 2024, 43(12), 1315-1333.
20. Connelly L. B, Woolf A. D & Hazes J. M. Cost-effectiveness of interventions for musculoskeletal conditions: A systematic review. Journal of Rheumatology. 2023, 30(8), 1788-1794.