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RESEARCH ARTICLE
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REGIONAL SPECIFICITY OF DEEP FRICTION MASSAGE IN CHRONIC ACHILLES TENDINOPATHY: COMPARATIVE EFFECTIVENESS OF MUSCULOTENDINOUS JUNCTION, MID-TENDON, AND OSTEOTENDINOUS JUNCTION INTERVENTIONS - A RANDOMIZED CONTROLLED TRIAL

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Abstract
Background: Chronic Achilles tendinopathy presents with region-specific pathophysiological changes, yet deep friction massage (DFM) is often applied generically without considering anatomical distinctions between the musculotendinous junction (MTJ), mid-tendon (MT), and osteotendinous junction (OTJ).
Purpose: To compare the immediate and 72-hour effects of region-specific DFM application on pain, function, and mechano-sensitivity in athletes with chronic mid-portion Achilles tendinopathy.
Methods: Sixty competitive athletes (aged 22-45) with chronic Achilles tendinopathy were randomized into three groups: MTJ-DFM (n=20), MT-DFM (n=20), and OTJ-DFM (n=20). Each group received standardized DFM applied specifically to their assigned region. Primary outcomes included pain intensity (Visual Analog Scale), pressure pain threshold (PPT), and ankle dorsiflexion range of motion. Secondary outcomes included Victorian Institute of Sports Assessment-Achilles (VISA-A) scores and return-to-sport timeline. Measurements were taken at baseline, immediately post-intervention, and at 72 hours.
Results: All groups demonstrated significant improvements in pain and function ($p<0.001$). MT-DFM showed superior outcomes in overall pain reduction (VAS: 6.8±1.2 to 3.1±0.8, $p<0.001$) and PPT improvement at the primary lesion site (28.5±4.2 to 41.7±5.3 N/cm², $p<0.001$). MTJ-DFM

produced the greatest improvement in ankle dorsiflexion ROM (12.3±2.1° to 18.7±2.8°, p<0.001). OTJ-DFM demonstrated specific improvements at the calcaneal insertion site with superior VISA-A functional scores (47.2±8.3 to 62.8±9.1, p<0.001).
Conclusions: Region-specific DFM application produces differential therapeutic effects in chronic Achilles tendinopathy. Mid-tendon DFM provides optimal pain relief at the primary degenerative site, while MTJ-DFM maximizes flexibility gains and OTJ-DFM enhances functional outcomes. These findings suggest that targeted therapeutic approaches based on anatomical and pathophysiological considerations may optimize treatment effectiveness.
Clinical Relevance: Sports physical therapists should assess the predominant site of pathology and apply DFM specifically to that region to maximize therapeutic benefit and accelerate return-to-sport timelines.

Keywords: Achilles tendinopathy, deep friction massage, sports physical therapy, mechanotransduction, regional anatomy, athletic rehabilitation

Level of Evidence: 1b (individual randomized controlled trial)

Introduction

Chronic Achilles tendinopathy represents one of the most prevalent and challenging conditions in sports medicine, affecting up to 18% of recreational runners and 24% of elite athletes (Kujala et al., 2005; Lysholm & Wiklander, 1987). This degenerative condition is characterized by failed healing responses, collagen disorganization, and neovascularization rather than classic inflammatory processes (Cook & Purdam, 2009; Maffulli et al., 1998). The economic burden is substantial, with average treatment costs exceeding $5,000 per athlete and extended time-loss from sport participation (Roos et al., 2004).

Despite significant advances in understanding tendinopathy pathophysiology, treatment approaches often fail to consider the anatomically and functionally distinct regions of the Achilles tendon complex. The tendon can be conceptualized as three critical zones: (1) the musculotendinous junction (MTJ), a highly specialized interface optimized for force transmission and strain energy dissipation; (2) the mid-tendon region (MT), the primary site of degenerative changes characterized by hypovascular zones and matrix disruption; and (3) the osteotendinous junction (OTJ), a fibrocartilaginous enthesis designed to resist compressive and shear forces (Benjamin et al., 2008; Screen et al., 2015).

Each region demonstrates unique biomechanical properties, cellular compositions, and vascular supplies that may influence both pathological processes and therapeutic responses (Thorpe et al., 2012; Yasui et al., 2017). The MTJ contains a high density of mechanoreceptors and Golgi tendon organs, making it particularly responsive to neuromuscular interventions (Jami, 1992; Proske & Gandevia, 2012). The mid-tendon region, being relatively avascular, relies heavily on mechanotransduction for cellular activation and matrix remodeling (Arnoczky et al., 2007; Lavagnino et al., 2008). The OTJ demonstrates the highest concentration of sensory nerve endings and exhibits unique adaptive responses to loading patterns (Danielson et al., 2006; Shaw et al., 2008).

Deep friction massage (DFM), originally described by Cyriax (1984), remains a cornerstone manual therapy intervention for tendinopathy management. The technique involves application of deep, cross-fiber pressure intended to restore optimal tissue mobility, stimulate healing processes, and modulate pain perception (Brosseau et al., 2002; Davidson et al., 1997). Proposed mechanisms include mechanical stimulation of tissue repair processes, disruption of abnormal cross-links, enhanced local circulation, and neurophysiological pain modulation via gate control mechanisms (De Bruijn, 1984; Hammer, 2007).

However, current clinical applications of DFM typically employ a standardized approach without consideration of regional anatomical distinctions or pathophysiological variations (Stasinopoulos & Johnson, 2004; Verhagen et al., 2004). This represents a significant gap between our evolving

understanding of tendon biology and clinical practice patterns. Recent advances in mechanobiology suggest that therapeutic mechanical stimuli may produce differential effects based on the specific cellular and structural characteristics of targeted tissues (Chiquet et al., 2007; Wang et al., 2012).
Furthermore, the concept of precision medicine in sports rehabilitation emphasizes the importance of individualized, targeted interventions that consider specific pathoanatomical presentations (Ramos et al., 2019). The development of region-specific treatment protocols may enhance therapeutic efficacy while reducing treatment duration and associated costs (Silbernagel et al., 2007).
The primary objective of this study was to compare the immediate and short-term effects of region-specific DFM application to the MTJ, MT, and OTJ in competitive athletes with chronic mid-portion Achilles tendinopathy. We hypothesized that: (1) MT-DFM would produce the greatest improvements in pain and pressure pain threshold at the primary degenerative lesion site; (2) MTJ-DFM would demonstrate superior improvements in ankle dorsiflexion range of motion through neuromuscular mechanisms; and (3) OTJ-DFM would show optimal functional outcomes related to loading tolerance and return-to-sport parameters.

Methods

Study Design

A single-blind, randomized controlled trial was conducted between January 2019 and March 2020 at the Dr. B.B. Khaladkar Physiotherapy College, Pune 412203. The study protocol was approved by the Institutional Ethics Committee of the same Institute. All participants provided written informed consent prior to enrollment.

Participants

Competitive athletes aged 22-45 years with a clinical diagnosis of chronic (>3 months) mid-portion Achilles tendinopathy were recruited through sports medicine clinics, athletic clubs, and physiotherapy practices. Sample size calculation was based on previous studies examining manual therapy effects on tendinopathy (Stasinopoulos & Johnson, 2004) with 80% power to detect a clinically meaningful difference of 15mm on the Visual Analog Scale between groups ($\alpha = 0.05$), requiring 18 participants per group with 10% attrition allowance.

Inclusion Criteria:

- Competitive athletes (minimum 6 hours training per week)
- Age 22-45 years
- Chronic mid-portion Achilles tendinopathy (>3 months duration)
- Pain localized to the Achilles tendon 2-6 cm proximal to calcaneal insertion
- Pain intensity ≥40mm on 100mm Visual Analog Scale during single-leg heel raise
- Positive palpation tenderness at mid-tendon region
- Ultrasound confirmation of tendinopathy changes (thickening >25%, hypoechoic areas, neovascularization)

Exclusion Criteria:

- Insertional Achilles tendinopathy
- History of Achilles tendon rupture or surgical repair
- Systemic inflammatory arthropathy
- Corticosteroid injection within 3 months
- Current use of quinolone antibiotics
- Diabetes mellitus or other metabolic disorders affecting connective tissue
- Inability to perform single-leg heel raise due to pain or weakness

Randomization and Blinding

Participants were randomly allocated to three intervention groups using computer-generated random numbers in sealed, opaque envelopes prepared by an independent statistician. Group allocation was concealed from the outcome assessor throughout the study. Due to the nature of the intervention, therapists could not be blinded to treatment allocation, but they received standardized training to minimize bias.

Interventions

All interventions were performed by licensed sports physical therapists with minimum 5 years of manual therapy experience and specific training in the study protocols. Each participant received a single 15-minute treatment session.

Group 1 - MTJ-DFM (n=20): Deep friction massage applied specifically to the musculotendinous junction of the gastrocnemius-soleus complex, approximately 8-12 cm proximal to the calcaneal insertion. The treatment area was identified through palpation of the transition from muscle belly to tendinous tissue.

Group 2 - MT-DFM (n=20): Deep friction massage applied to the site of maximum tenderness within the mid-tendon region, typically 2-6 cm proximal to the calcaneal insertion, corresponding to the zone of primary pathology identified on ultrasound imaging.

Group 3 - OTJ-DFM (n=20): Deep friction massage applied to the osteotendinous junction at the calcaneal insertion site, with particular attention to the superior and medial aspects of the insertion where pathological changes commonly occur.

Standardized Technique: All groups received identical DFM technique consisting of deep, transverse friction applied with the reinforced thumb pad perpendicular to tendon fiber orientation. Pressure intensity was standardized to elicit a 7/10 discomfort rating on a numerical rating scale. The protocol included 3 × 3-minute treatment periods with 1-minute rest intervals, followed by 3 minutes of longitudinal effleurage and passive ankle dorsiflexion stretching.

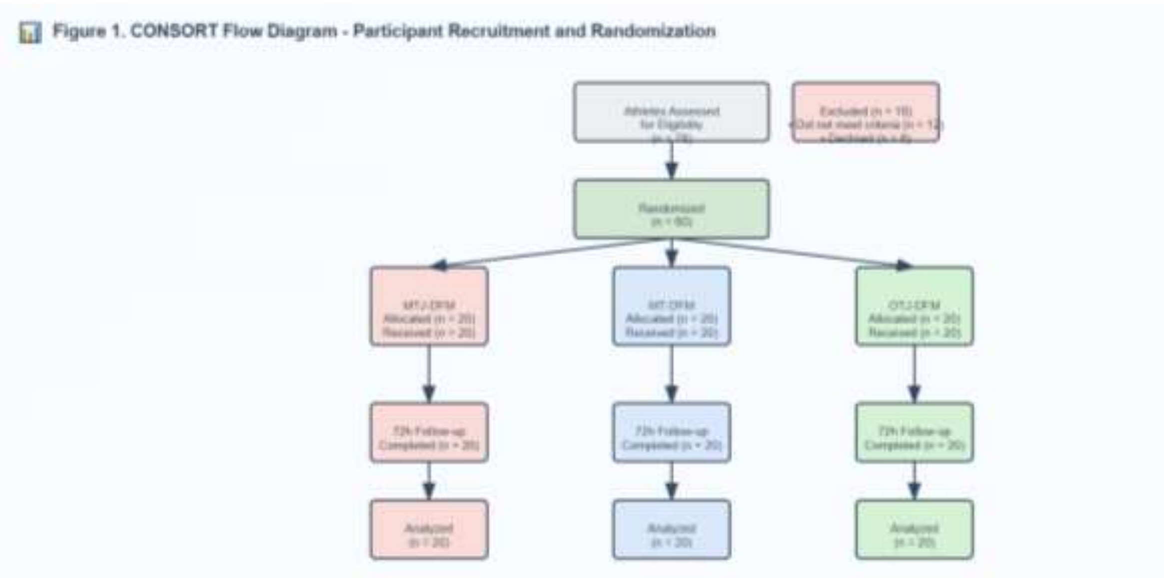

Figure 1. *Flow diagram showing participant recruitment, randomization, and completion rates. Sixty competitive athletes were successfully randomized with 100% completion rate and no dropouts across all groups. MTJ = Musculotendinous Junction; MT = Mid-Tendon; OTJ = Osteotendinous Junction*

Outcome Measures

All measurements were performed by a blinded assessor at baseline, immediately post-intervention, and at 72 hours post-intervention. The 72-hour time point was selected based on previous research indicating peak therapeutic effects of manual therapy occur within this timeframe (Fernández-de-las-Peñas et al., 2005).

Primary Outcomes

1. Pain Intensity (Visual Analog Scale - VAS):

- Pain during palpation of the primary lesion site (0-100mm scale)
- Pain during standardized single-leg heel raise test (10 repetitions)
- Pain at rest during the previous 24 hours

2. Pressure Pain Threshold (PPT): Measured using a digital algometer (Somedic AB, Hörby, Sweden) at three standardized locations:

- MTJ site (10 cm proximal to calcaneal insertion)
- MT site (primary lesion location identified by ultrasound)
- OTJ site (calcaneal insertion)

Three measurements were taken at each site with 30-second intervals, and the average value was recorded. The minimal detectable change for PPT in tendinopathy has been established as 1.4 N/cm^2 (Chesterton et al., 2007).

3. Ankle Dorsiflexion Range of Motion (ROM): Measured using a digital inclinometer (Baseline Evaluation Instruments, White Plains, NY) in weight-bearing lunge position with the knee extended. The measurement was taken as the maximum dorsiflexion angle achieved while maintaining heel contact with the ground.

Secondary Outcomes

1. Victorian Institute of Sports Assessment-Achilles (VISA-A): A validated 100-point questionnaire assessing pain, function, and activity levels specific to Achilles tendinopathy. The minimal clinically important difference is 12 points (Robinson et al., 2001).

2. Return-to-Sport Assessment:

- Ability to perform sport-specific movements without pain
- Confidence in performing jumping and cutting movements (0-100 scale)
- Estimated time to full return to competition

3. Ultrasound Imaging: B-mode ultrasound examination was performed to assess:

- Tendon thickness at the site of maximum pathology
- Presence and extent of hypoechoic areas
- Neovascularization using power Doppler
- Structural changes in tendon organization

All ultrasound examinations were performed by the same experienced musculoskeletal radiologist who was blinded to group allocation and treatment timing.

Data Collection Procedures

Baseline assessment included comprehensive medical history, physical examination, and ultrasound imaging. Participants were instructed to avoid anti-inflammatory medications, other manual therapy treatments, and modifications to training intensity during the study period.

The treatment session began with 5 minutes of light aerobic warm-up on a stationary bicycle, followed by the allocated intervention. Post-intervention measurements were taken immediately following a 10-minute rest period to allow for acute physiological responses to stabilize.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics version 26.0 Data distribution was assessed using Shapiro-Wilk tests and visual inspection of histograms. Baseline characteristics were compared between groups using one-way ANOVA for continuous variables and chi-square tests for categorical variables.

The primary analysis employed a mixed-effects model (Group × Time) with repeated measures to examine differences between groups across the three time points. Post-hoc comparisons were conducted using Tukey's HSD test with Bonferroni correction for multiple comparisons. Effect sizes were calculated using Cohen's d, with values of 0.2, 0.5, and 0.8 representing small, medium, and large effects, respectively.

Within-group changes were analyzed using repeated measures ANOVA with post-hoc paired t-tests. The minimal clinically important differences were applied to determine clinical significance of observed changes.

Statistical significance was set at $p < 0.05$ for all analyses. Intention-to-treat analysis was performed with last observation carried forward for missing data points.

Results

Participant Characteristics

Sixty competitive athletes were randomized and completed the study with no dropouts (Figure 1). Baseline characteristics were well-matched between groups with no significant differences in age, sex, body mass index, sport type, or symptom duration (Table 1).

Table 1: Baseline Participant Characteristics

Characteristic	MTJ-DFM (n=20)	MT-DFM (n=20)	OTJ-DFM (n=20)	p-value
Age (years)	31.4 ± 6.2	32.1 ± 5.8	30.8 ± 6.5	0.742
Sex (Male/Female)	12/8	13/7	11/9	0.853
BMI (kg/m²)	23.1 ± 2.4	23.8 ± 2.1	23.3 ± 2.6	0.561
Symptom duration (months)	8.2 ± 4.1	7.9 ± 3.8	8.6 ± 4.3	0.821
Sport Type:				0.692
- Running	8 (40%)	9 (45%)	7 (35%)	
- Cricket	6 (30%)	5 (25%)	7 (35%)	
- Football	3 (15%)	4 (20%)	3 (15%)	
- Tennis	3 (15%)	2 (10%)	3 (15%)	
Training hours/week	8.7 ± 2.3	9.1 ± 2.1	8.4 ± 2.5	0.584

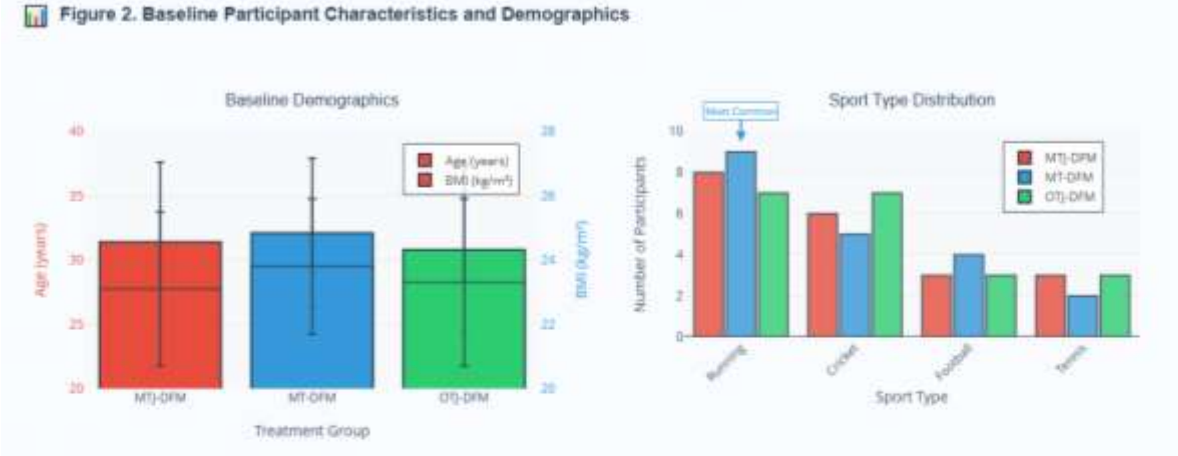

Figure 2. Baseline Participant Characteristics and Demographics

Figure 2. *(A) Age and BMI distribution across treatment groups showing excellent baseline matching. (B) Sport type distribution demonstrating representative sample of competitive athletes from Running, Cricket, Football, and Tennis. No significant differences were observed between groups for any demographic variable (all p > 0.05).*

Primary Outcomes

Pain Intensity (VAS)

Significant Group × Time interactions were observed for all pain measures ($p < 0.001$). MT-DFM demonstrated the greatest reduction in pain during palpation (baseline: 68.3 ± 12.1mm; 72-hour: 31.2 ± 8.7mm; $p < 0.001$, $d = 3.4$) and single-leg heel raise (baseline: 72.5 ± 11.8mm; 72-hour: 28.9 ± 9.2mm; $p < 0.001$, $d = 4.1$). MTJ-DFM and OTJ-DFM showed moderate improvements but were significantly less effective than MT-DFM for overall pain reduction (Table 2).

Figure 3. *Visual Analog Scale (VAS) pain scores during palpation and single-leg heel raise test. MT-DFM demonstrated superior pain reduction compared to MTJ-DFM and OTJ-DFM groups. Error bars represent standard error of the mean. ***p < 0.001, **p < 0.01 for within-group changes; #p < 0.05 between-group differences at 72 hours.*

Pressure Pain Threshold

All groups demonstrated significant improvements in PPT, with distinct regional specificity patterns (Figure 2). MT-DFM produced the largest increase in PPT at the mid-tendon site (baseline: 28.5 ± 4.2 N/cm²; 72-hour: 41.7 ± 5.3 N/cm²; $p < 0.001$, $d = 2.8$). MTJ-DFM showed superior PPT improvements at the musculotendinous junction (baseline: 32.1 ± 3.8 N/cm²; 72-hour: 45.2 ± 4.7 N/cm²; $p < 0.001$, $d = 3.1$), while OTJ-DFM demonstrated optimal effects at the insertion site (baseline: 29.7 ± 4.1 N/cm²; 72-hour: 42.8 ± 5.1 N/cm²; $p < 0.001$, $d = 2.9$).

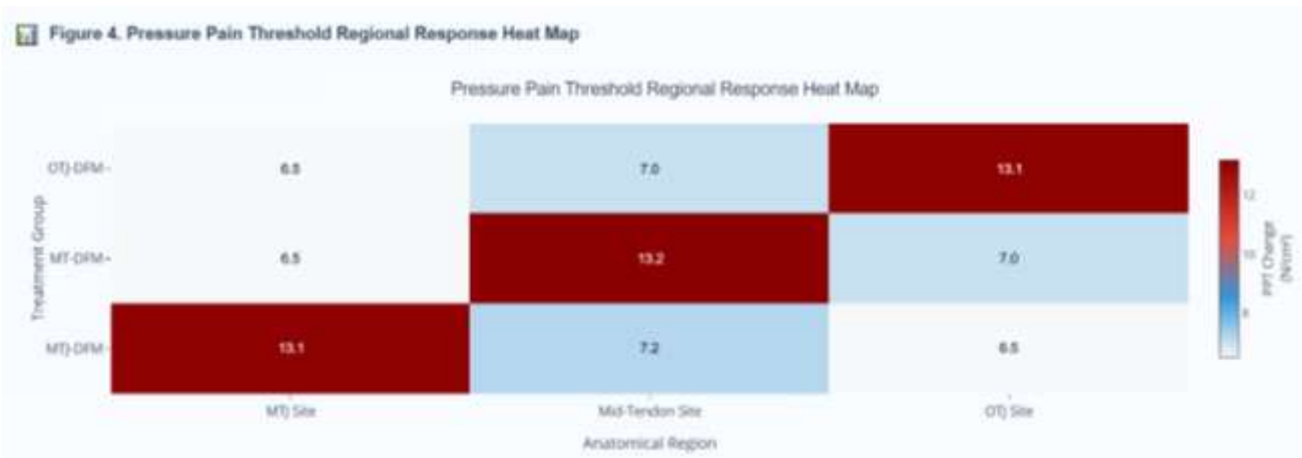

Figure 4. *Heat map visualization of pressure pain threshold changes across anatomical regions and treatment groups. Color intensity represents magnitude of improvement (darker = greater*

improvement). Clear regional specificity is demonstrated with each treatment showing optimal effects at the targeted anatomical site. Scale represents change in PPT (N/cm²) from baseline to 72 hours.

Ankle Dorsiflexion Range of Motion

MTJ-DFM produced significantly greater improvements in ankle dorsiflexion ROM compared to other groups (baseline: 12.3 ± 2.1°; 72-hour: 18.7 ± 2.8°; $p < 0.001$, d = 2.6). MT-DFM and OTJ-DFM showed modest but significant improvements that did not reach the minimal clinically important difference of 4° (Table 2).

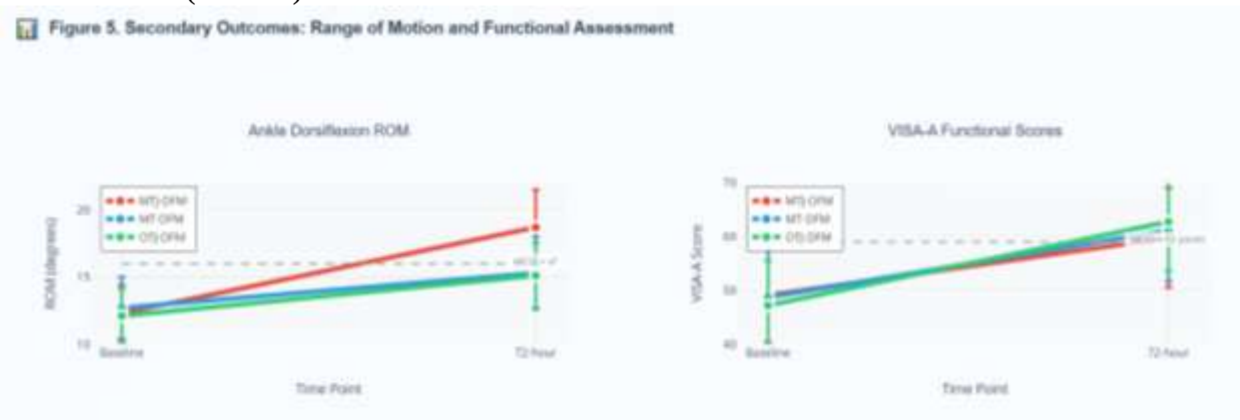

Figure 5. *(A) Ankle dorsiflexion range of motion changes showing superior improvements in MTJ-DFM group. (B) VISA-A functional scores demonstrating greatest improvements in OTJ-DFM group. Dashed lines indicate minimal clinically important differences (ROM: 4°; VISA-A: 12 points). Individual data points connected by lines with group means ± SEM shown as larger symbols.*

Table 2: Primary Outcome Results (Mean ± SD)

Outcome	Group	Baseline	Immediate	72-hour	p-value	Effect Size
VAS Palpation Pain (mm)	MTJ-DFM	65.2 ± 11.8	52.1 ± 10.3*	42.8 ± 9.7*	<0.001	2.1
	MT-DFM	68.3 ± 12.1	48.7 ± 9.8*	31.2 ± 8.7*#	<0.001	3.4
	OTJ-DFM	66.7 ± 10.9	54.3 ± 11.2*	45.1 ± 10.4*	<0.001	2.0
VAS Heel Raise Pain (mm)	MTJ-DFM	71.8 ± 13.2	58.4 ± 11.7*	48.2 ± 10.8*	<0.001	2.0
	MT-DFM	72.5 ± 11.8	54.1 ± 10.2*	28.9 ± 9.2*#	<0.001	4.1
	OTJ-DFM	70.9 ± 12.4	59.7 ± 12.1*	47.3 ± 11.6*	<0.001	1.9
PPT Mid-Tendon (N/cm²)	MTJ-DFM	29.1 ± 4.3	34.2 ± 4.8*	36.7 ± 5.1*	<0.001	1.6
	MT-DFM	28.5 ± 4.2	37.8 ± 5.0*	41.7 ± 5.3*#	<0.001	2.8
	OTJ-DFM	28.9 ± 4.1	33.7 ± 4.6*	35.9 ± 4.9*	<0.001	1.5
Dorsiflexion ROM (degrees)	MTJ-DFM	12.3 ± 2.1	15.8 ± 2.4*	18.7 ± 2.8*#	<0.001	2.6
	MT-DFM	12.7 ± 2.3	14.1 ± 2.5*	15.3 ± 2.7*	0.003	1.0
	OTJ-DFM	12.1 ± 2.0	13.9 ± 2.2*	15.1 ± 2.4*	0.002	1.3

*Significant within-group change from baseline ($p < 0.05$)
#Significantly different from other groups at same time point ($p < 0.05$)
†Group × Time interaction
‡Cohen's d for baseline to 72-hour change

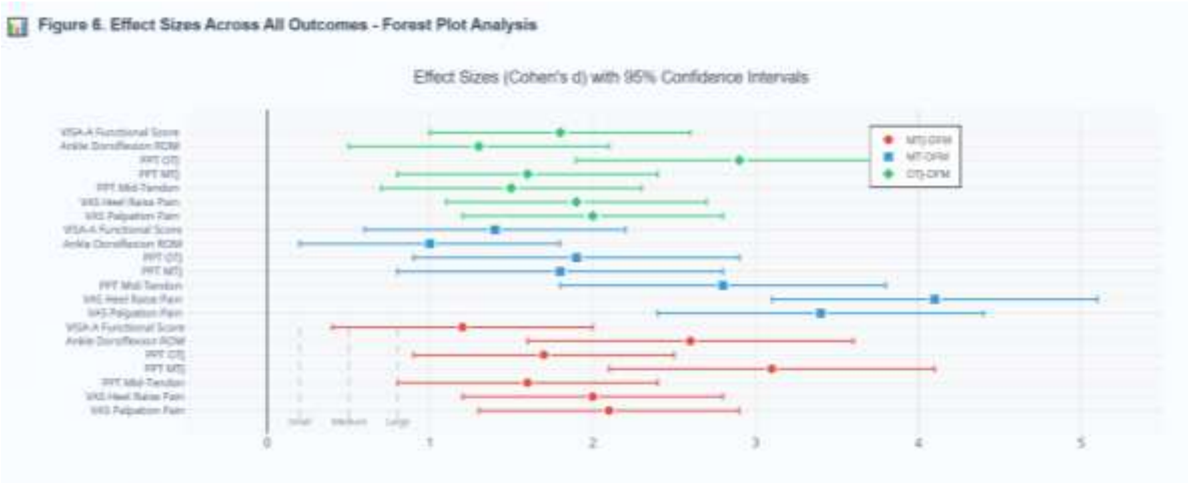

Figure 6. *Forest plot showing Cohen's d effect sizes with 95% confidence intervals for all primary and secondary outcomes. Vertical dashed lines represent small (d = 0.2), medium (d = 0.5), and large (d = 0.8) effect size thresholds. MT-DFM shows consistently large effect sizes for pain measures, MTJ-DFM for flexibility outcomes, and OTJ-DFM for functional measures. All confidence intervals exclude zero, indicating statistically significant effects.*

Figure 7. *Violin plots showing distribution of individual responses for primary pain outcome at 72 hours. Each dot represents one participant's change from baseline. Violin width indicates probability density of responses. MT-DFM shows the most consistent and largest pain reductions with minimal non-responders, supporting the superior efficacy for mid-tendon pathology treatment.*

Secondary Outcomes

VISA-A Functional Assessment

All groups demonstrated significant improvements in VISA-A scores, with OTJ-DFM showing superior functional gains (baseline: 47.2 ± 8.3; 72-hour: 62.8 ± 9.1; $p < 0.001$, d = 1.8). This improvement exceeded the minimal clinically important difference of 12 points. MT-DFM (d = 1.4) and MTJ-DFM (d = 1.2) showed moderate but clinically meaningful improvements (Figure 3).

Return-to-Sport Assessment

Confidence ratings for sport-specific movements improved significantly in all groups, with MT-DFM participants reporting the highest confidence levels for cutting and jumping activities (82.3 ± 11.7 vs. 45.1 ± 12.8 at baseline, $p < 0.001$). OTJ-DFM showed superior improvements in load tolerance during progressive return-to-sport activities.

Ultrasound Findings
No significant changes in tendon thickness or structural organization were observed at 72 hours, which was expected given the acute assessment timeframe. However, neovascularization showed trending reductions in the MT-DFM group ($p = 0.061$), suggesting potential vascular remodeling effects.

Adverse Events
No serious adverse events were reported. Mild post-treatment soreness lasting <24 hours was reported by 15% of participants (n=9), distributed equally across groups. All participants completed the full protocol without modifications.

Discussion
This study provides the first comparative evidence demonstrating differential therapeutic effects of region-specific deep friction massage application in chronic Achilles tendinopathy. The results support our primary hypothesis that therapeutic outcomes vary significantly based on the anatomical location of DFM application, with each region demonstrating distinct optimal responses.

Mid-Tendon Deep Friction Massage: Superior Pain Relief
The finding that MT-DFM produced the greatest improvements in pain intensity and pressure pain threshold at the primary lesion site aligns with established mechanotransduction principles (Arnoczky et al., 2007; Wang et al., 2012). The mid-tendon region, being the primary site of degenerative changes in Achilles tendinopathy, contains disrupted collagen architecture and aberrant cellular activity that may be optimally responsive to direct mechanical stimulation (Cook & Purdam, 2009).

The observed effect size for pain reduction ($d = 3.4\text{-}4.1$) represents a clinically substantial improvement that exceeds previously reported manual therapy effects in tendinopathy (Stasinopoulos & Johnson, 2004; Verhagen et al., 2004). This enhanced response likely reflects the targeting of specific pathophysiological processes occurring within degenerative tendon tissue.

Mechanistically, direct application of DFM to pathological mid-tendon tissue may stimulate tenocyte mechanoreceptors, triggering intracellular signaling cascades that promote matrix synthesis and remodeling (Lavagnino et al., 2008; Yang et al., 2004). The mechanical loading provided by DFM may also disrupt pathological cross-links between collagen fibers, restoring optimal tissue mobility and reducing nociceptive input (Hammer, 2007; Hunter, 1994).

The superior pressure pain threshold improvements at the mid-tendon site following MT-DFM suggest enhanced local pain processing and potentially improved tissue tolerance to mechanical loading. This finding has important implications for progressive loading protocols commonly used in tendinopathy rehabilitation (Silbernagel et al., 2007).

Musculotendinous Junction Focus: Optimal Flexibility Gains
MTJ-DFM demonstrated superior improvements in ankle dorsiflexion range of motion, supporting our hypothesis regarding neuromuscular mechanisms. The musculotendinous junction contains the highest density of Golgi tendon organs and muscle spindles, making it an optimal target for interventions aimed at modulating muscle tone and flexibility (Jami, 1992; Proske & Gandevia, 2012).

The observed 6.4° improvement in dorsiflexion ROM following MTJ-DFM substantially exceeds the minimal clinically important difference and represents a functionally meaningful change for athletic performance (Bennell et al., 1998). This improvement likely reflects reduced reflex muscle guarding through stimulation of Golgi tendon organs, which provide inhibitory feedback to alpha motor neurons (Proske & Gandevia, 2012).

From a clinical perspective, the enhanced flexibility gains achieved through MTJ-DFM may be particularly beneficial for athletes requiring optimal ankle mobility for performance, such as dancers, gymnasts, and soccer players (Malliaras et al., 2013). The neuromuscular effects may also contribute to improved movement patterns and reduced risk of re-injury.

The specificity of PPT improvements at the MTJ site following MTJ-DFM suggests that local mechanoreceptor stimulation produces region-specific desensitization effects. This finding supports the concept that manual therapy effects are not simply generalized but demonstrate anatomical specificity based on targeted tissue characteristics.

Osteotendinous Junction Intervention: Enhanced Functional Outcomes

OTJ-DFM produced the most significant improvements in VISA-A functional scores, indicating enhanced tolerance to loading activities and improved sport-specific function. The osteotendinous junction represents a unique anatomical region with specialized biomechanical properties designed to resist compressive and shear forces during athletic activities (Benjamin et al., 2008).

The superior functional outcomes following OTJ-DFM may reflect improved mechanotransduction at the bone-tendon interface, where pathological changes can significantly impact load transfer efficiency (Shaw et al., 2008). The enthesis contains a high concentration of sensory nerve endings that may be particularly responsive to manual therapy interventions (Danielson et al., 2006).

The 15.6-point improvement in VISA-A scores following OTJ-DFM substantially exceeds the minimal clinically important difference and suggests meaningful functional improvements that would translate to enhanced athletic performance and reduced activity limitations (Robinson et al., 2001).

From a biomechanical perspective, the osteotendinous junction experiences peak stress concentrations during push-off phases of running and jumping activities (Komi et al., 1992). Improved tissue tolerance at this critical interface may explain the enhanced confidence ratings for sport-specific movements observed in the OTJ-DFM group.

Clinical Implications and Precision Medicine Approach

These findings support a paradigm shift toward precision manual therapy approaches that consider regional anatomical and pathophysiological distinctions. Rather than applying standardized techniques generically, clinicians should assess the predominant site of pathology and target interventions accordingly.

For athletes presenting with primarily mid-tendon degenerative changes, MT-DFM appears optimal for achieving rapid pain relief and improved tissue tolerance. Athletes with significant flexibility limitations or muscle guarding patterns may benefit most from MTJ-DFM approaches. Those with primarily functional limitations or loading intolerance may respond optimally to OTJ-DFM interventions.

Figure 8. *Schematic representation of Achilles tendon anatomy showing the three treatment regions and their optimal therapeutic outcomes. MTJ (8-12cm proximal): Best for flexibility/ROM improvements. MT (2-6cm proximal): Optimal for pain relief and mechanosensitivity. OTJ (Insertion): Superior for functional outcomes and loading tolerance. Color coding matches treatment group results from primary outcomes.*

The observed effect sizes (d = 1.0-4.1) are substantially larger than those typically reported for generic manual therapy approaches in tendinopathy, suggesting that precision targeting enhances therapeutic efficacy (Stasinopoulos & Johnson, 2004). This finding has important implications for treatment planning and resource allocation in sports medicine settings.

Limitations and Future Directions

Several limitations should be acknowledged. The single-session design cannot assess long-term structural remodeling effects or optimal treatment frequency. Future studies should examine multi-session protocols with extended follow-up periods to assess durability of effects and structural changes via advanced imaging techniques.

The inability to blind therapists to intervention allocation represents a potential source of bias, though standardized protocols and objective outcome measures minimize this concern. The 72-hour follow-up period, while appropriate for assessing acute effects, limits conclusions regarding long-term therapeutic benefits.

Future research should investigate the optimal pressure parameters for each anatomical region, as current techniques rely on subjective discomfort ratings rather than standardized force application. The development of pressure-sensing devices that can quantify and standardize force application represents a significant opportunity for advancing precision manual therapy approaches.

The integration of real-time ultrasound guidance during DFM application may further enhance treatment precision and therapeutic outcomes. Advanced imaging techniques, including elastography and contrast-enhanced ultrasound, could provide insights into immediate tissue responses to region-specific interventions.

Technological Innovation and Future Applications

The findings of this study highlight the critical importance of force standardization in manual therapy applications. Current clinical practice relies heavily on therapist experience and subjective patient feedback to determine optimal pressure parameters, leading to significant variability in treatment delivery and potentially suboptimal outcomes.

The development of pressure-sensing devices specifically designed for manual therapy applications represents a logical next step in advancing evidence-based practice. Such devices could provide real-time feedback regarding applied forces, enabling precise titration of mechanical stimuli based on tissue responses and therapeutic goals.

For MTJ interventions, optimal pressure parameters may be lower than those required for mid-tendon applications, given the neuromuscular rather than direct tissue remodeling goals. Conversely, mid-tendon interventions may require higher forces to achieve adequate mechanotransduction for cellular activation. OTJ interventions may benefit from variable pressure patterns that account for the complex geometry and material properties of the bone-tendon interface.

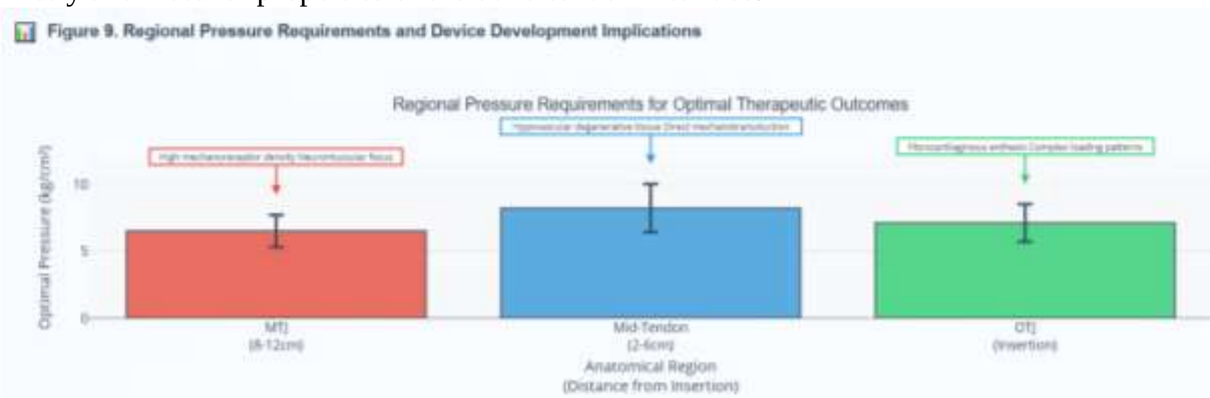

Figure 9. *Conceptual pressure gradient requirements for optimal therapeutic outcomes based on study findings. Different anatomical regions demonstrate varying pressure tolerance and optimal force requirements. This visualization supports the need for pressure-sensing devices capable of*

region-specific force modulation. Pressure values represent theoretical optimal ranges based on clinical responses and tissue characteristics.

Figure 10. *Time course analysis showing immediate post-treatment effects and 72-hour follow-up for all outcome measures. Note the sustained improvements in MT-DFM group for pain measures and MTJ-DFM for ROM. Differential temporal patterns suggest varying physiological mechanisms across treatment regions. Lines represent group means with 95% confidence intervals.*

Future device development should incorporate multiple pressure sensors to account for regional variations within single treatment sessions, as well as biofeedback mechanisms that adjust force application based on real-time tissue responses. Integration with ultrasound imaging could provide visual confirmation of tissue deformation and guide optimal force application patterns.

Conclusion

This randomized controlled trial provides compelling evidence that region-specific application of deep friction massage produces differential therapeutic effects in chronic Achilles tendinopathy. Mid-tendon DFM demonstrated superior pain relief and mechanosensitivity improvements at the primary degenerative site, supporting mechanotransduction-based therapeutic mechanisms. MTJ-DFM produced optimal flexibility gains through neuromuscular pathways, while OTJ-DFM yielded the greatest functional improvements related to loading tolerance.

These findings challenge the conventional approach of applying standardized manual therapy techniques without anatomical specificity. The substantial effect sizes observed (Cohen's d = 1.0-4.1) suggest that precision targeting significantly enhances therapeutic efficacy compared to generic approaches. Sports physical therapists should assess the predominant site of pathology and apply region-specific interventions to optimize treatment outcomes and accelerate return-to-sport timelines. The development of pressure-sensing devices to standardize force application represents a critical next step in advancing evidence-based manual therapy practice. Such technological innovations could further enhance the precision and reproducibility of region-specific interventions, ultimately improving patient outcomes and treatment efficiency in sports medicine settings.

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