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SENSOR-BASED INTELLIGENT REHABILITATION VERSUS PNF FOR FUNCTIONAL ANKLE INSTABILITY: A RANDOMIZED CONTROLLED TRIAL

Original Research (ID: 1685)

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ABSTRACT

Background: Functional ankle instability is a frequent consequence of ankle injury and may lead to recurrent giving way, pain, impaired balance, and reduced functional performance. Conventional rehabilitation approaches such as proprioceptive neuromuscular facilitation are commonly used to improve neuromuscular control, while sensor-based intelligent rehabilitation provides real-time feedback and objective movement correction. Comparing these approaches may help identify a more effective rehabilitation strategy for improving clinical outcomes in adults with functional ankle instability.

Objective: To compare the effects of sensor-based intelligent rehabilitation and proprioceptive neuromuscular facilitation on pain, functional disability, and dynamic balance among adults with functional ankle instability.

Methods: This single-blinded randomized controlled trial was conducted over six months at Chaudhry Muhammad Akram Teaching and Research Hospital, Lahore. A total of 66 participants were enrolled through non-probability purposive sampling and randomly allocated into two equal groups using the lottery method. Group A received sensor-based intelligent rehabilitation using smart insole-guided balance and ankle-control exercises, while Group B received proprioceptive neuromuscular facilitation. Both interventions were delivered over four weeks. Pain was assessed using the Visual Analogue Scale, functional disability through the Foot and Ankle Disability Index, and dynamic balance through the Y Balance Test. Data were analyzed using SPSS version 27.0.

Results: The mean age was 28.15 ± 4.62 years in Group A and 26.64 ± 5.10 years in Group B. Post-treatment VAS scores were significantly lower in Group A than Group B (3.60 ± 1.60 vs. 4.45 ± 1.42, $p = 0.026$). FADI scores were significantly higher in Group A than Group B (65.88 ± 7.27 vs. 62.00 ± 5.79, $p = 0.019$). Y Balance Test scores also showed significantly greater improvement in Group A compared with Group B (79.66 ± 3.54 vs. 76.93 ± 3.70, $p = 0.003$).

Conclusion: Sensor-based intelligent rehabilitation produced greater improvement in pain, disability, and dynamic balance than proprioceptive neuromuscular facilitation, suggesting its practical value as an effective rehabilitation approach for functional ankle instability.

Keywords: Ankle Injuries; Ankle Joint; Exercise Therapy; Pain; Postural Balance; Proprioception; Rehabilitation

INTRODUCTION

Functional ankle instability is a common and clinically important problem that often develops after ankle sprain and may continue even when the initial ligament injury has apparently healed. The ankle joint, formed mainly by the tibia, fibula, and talus, works together with the subtalar and distal tibiofibular joints to provide controlled movement, weight bearing, and stability during walking, running, landing, and direction-changing activities (1). Stability of this joint does not depend only on passive ligaments and bony alignment; it also relies on an efficient sensorimotor system. Mechanoreceptors located in the ligaments, tendons, joint capsule, and skin continuously provide proprioceptive information to the central nervous system, allowing rapid muscular responses that protect the ankle from excessive inversion, abnormal loading, and recurrent injury (2). When these sensory and motor control mechanisms are disturbed after injury, the individual may experience repeated episodes of giving way, pain, impaired balance, reduced confidence during movement, and difficulty performing daily or sport-related activities. This clinical presentation is commonly described as functional ankle instability. Its prevalence varies depending on the population and diagnostic criteria used, but it remains particularly common among physically active individuals, with epidemiological reports suggesting a prevalence of approximately one-fourth in active populations (3). The condition is therefore not only a localized ankle problem but also a functional limitation that can affect mobility, participation, physical performance, and quality of life.

The pathophysiology of functional ankle instability involves both peripheral and central mechanisms. Injury to the lateral ankle structures may damage mechanoreceptors and reduce the accuracy of joint position sense and movement detection. As a result, corrective muscle activation may become delayed or insufficient, while anticipatory postural control may shift toward greater visual dependence and compensatory proximal strategies (4). Over time, these altered movement patterns may become habitual because of changes in spinal, cortical, and subcortical motor control. This can lead to persistent abnormal inversion angles, asymmetrical loading, poor dynamic balance, and repeated episodes of ankle giving way despite apparent tissue recovery (5). For this reason, effective rehabilitation should not only focus on pain relief and strength restoration but should also address proprioception, neuromuscular coordination, postural control, and functional movement retraining. Conservative rehabilitation remains the main approach for functional ankle instability. Standard physiotherapy usually progresses from range of motion exercises, strengthening of the ankle invertors and evertors, and flexibility training toward balance, perturbation, agility, and sport-specific neuromuscular training (6). Proprioceptive neuromuscular facilitation is one of the established rehabilitation techniques used to improve coordinated muscle activation through diagonal and rotational movement patterns, graded manual resistance, stretch, rhythmic stabilization, and functional movement control (7). Through mechanisms such as muscle spindle facilitation, reciprocal inhibition, irradiation, and improved motor recruitment, PNF may enhance ankle control during weight bearing, gait, and dynamic balance activities. However, as PNF is largely therapist-guided, the precision of feedback, progression, and performance monitoring may vary across sessions and clinical settings.

In recent years, sensor-based intelligent rehabilitation has emerged as a promising approach for improving neuromuscular rehabilitation. Wearable inertial sensors, smart insoles, pressure sensors, and instrumented balance platforms can measure joint motion, plantar pressure distribution, loading symmetry, postural sway, and movement timing during rehabilitation tasks (8,9). These systems provide real-time visual, auditory, or haptic feedback, helping patients recognize movement errors and correct them immediately. Such feedback may support motor learning by making rehabilitation more interactive, measurable, and individualized. In functional ankle instability, sensor-based rehabilitation may help reduce excessive inversion, improve weight-shifting control, normalize balance strategies, and enhance corrective responses during functional tasks (10). This is particularly relevant because patients with ankle instability often need repeated practice with accurate feedback to regain confidence and automatic control during daily and athletic movements. Although both PNF and sensor-based rehabilitation are theoretically beneficial for functional ankle instability, direct comparison between these two approaches remains limited. Previous research has reported the value of proprioceptive and balance-based training in improving ankle stability, while newer studies have highlighted the potential role of wearable sensors and intelligent feedback systems in rehabilitation (8-11). However, many available studies are limited by small samples, variable intervention protocols, short follow-up periods, or a focus on diagnostic and biomechanical outcomes rather than clinically meaningful outcomes such as pain, disability, and dynamic balance. In addition, the practical superiority of sensor-based rehabilitation over therapist-guided PNF has not been clearly established in adults with functional ankle instability.

This gap is important because clinicians require evidence not only about whether a treatment works, but also about which approach produces greater functional improvement within a practical rehabilitation period. If sensor-based intelligent rehabilitation provides superior improvement in pain, disability, and balance, it may support more objective, engaging, and patient-centered rehabilitation for individuals with functional ankle instability. Conversely, if its effects are comparable to PNF, then conventional therapist-led rehabilitation may remain a practical and cost-effective option in many clinical settings. Therefore, this randomized controlled trial was conducted to compare the effects of sensor-based intelligent rehabilitation and proprioceptive neuromuscular facilitation on pain, disability, and dynamic balance among adults with functional ankle instability. The study was based on the hypothesis that sensor-based intelligent rehabilitation would produce greater improvement in pain reduction, functional ability, and dynamic balance compared with PNF because of its real-time feedback, objective performance monitoring, and adaptive movement correction during rehabilitation.

METHODS

This single-blinded randomized controlled trial was conducted at Chaudhry Muhammad Akram Teaching and Research Hospital, Lahore, over a period of six months after approval from the Institutional Review Board/Ethical Review Committee. All participants were informed about the purpose, procedures, potential benefits, and possible risks of the study before enrolment, and written informed consent was obtained. Confidentiality of participant information was maintained throughout the study, and participants were allowed to withdraw from the trial at any stage without any effect on their routine care. A total of 66 participants with functional ankle instability were enrolled through a non-probability purposive sampling technique and randomly allocated into two equal groups using the lottery method. Group A consisted of 33 participants who received sensor-based intelligent rehabilitation, while Group B consisted of 33 participants who received proprioceptive neuromuscular facilitation. No participant dropped out during the study; therefore, data from all 66 participants were included in the final analysis. The trial was described as single-blinded because the outcome assessor was kept unaware of group allocation, as participant blinding was not practically possible due to the visible difference between smart insole-based rehabilitation and therapist-administered PNF (12).

Both male and female participants aged 20 to 35 years with unilateral functional ankle instability were included in the study. Participants were eligible if they had a body mass index between 18 and 25 kg/m², had not participated in any structured ankle rehabilitation program during the previous six months, and fulfilled the clinical criteria for functional ankle instability using the Cumberland Ankle Instability Tool. Participants with bilateral ankle sprain, recent lower limb fracture or surgery within the previous six months, visual impairment affecting balance, congenital deformity of the spine, ankle, foot, or knee, lower extremity pathological symptoms, or medical conditions requiring close monitoring, such as heart disease, uncontrolled hypertension, or uncontrolled diabetes, were excluded from the study (13,14). Baseline assessment was performed before the start of treatment, and post-treatment assessment was carried out after completion of the four-week intervention. Demographic information, including age, height, weight, gender, and affected side, was recorded. The main outcome measures were pain intensity, functional disability, and dynamic balance. Pain was assessed using the Visual Analogue Scale, functional status was measured through the Foot and Ankle Disability Index, and dynamic balance was evaluated using the Y Balance Test. The Cumberland Ankle Instability Tool was used for screening and confirmation of ankle instability, although it was not included in the final reported outcome analysis.

Participants in Group A received sensor-based intelligent rehabilitation using the SALTED Smart Insole system. During treatment sessions, participants performed supervised balance and ankle-control exercises while wearing smart insoles that provided real-time feedback regarding plantar pressure distribution, weight shifting, ankle movement, and postural stability. Each session lasted 40 minutes and included static single-leg stance, dynamic lateral and anteroposterior weight shifting with inversion and eversion control, reactive perturbation training, and functional task integration. Static single-leg stance was performed as four holds of 45 seconds with 15 seconds of seated rest. Dynamic weight-shifting exercises were performed for three sets of 30 seconds with 30 to 45 seconds of rest. Reactive perturbation training included six trials of 20 to 30 seconds with 10 to 20 seconds of rest, while functional task training was performed in three rounds of 60 seconds each with 20 seconds of rest between rounds. Dual-task challenges were also incorporated during functional activities to simulate real-life movement demands (12). Participants in Group B received proprioceptive neuromuscular facilitation for the ankle. Each session lasted 40 minutes and was conducted four times per week for four weeks. The treatment included contract-relax techniques for dorsiflexion and plantarflexion, hold-relax techniques for inversion and eversion, diagonal lower-limb PNF patterns, standing balance-based PNF activities, and functional step and gait-transfer exercises. Contract-relax techniques were performed in supine or long-sitting positions, with an isometric contraction held for six to eight seconds at approximately 60% to 75% of maximal voluntary contraction, followed by two to three seconds of relaxation and movement to a new available range. Hold-relax techniques were applied for inversion and eversion control using therapist resistance, followed by passive range progression. Diagonal D1 and D2 lower-limb patterns were performed in controlled repetitions, while standing PNF exercises were integrated with foam or wobble-board balance challenges. Functional activities included step-ups and step-downs with emphasis on dorsiflexion control, inversion stability, and progressive resistance according to participant tolerance (15).

The Visual Analogue Scale was used to assess pain intensity on a scale from 0 to 10, where 0 represented no pain and 10 represented the worst possible pain. It is a commonly used clinical measure for pain assessment and has acceptable reliability and validity in musculoskeletal conditions (16). The Foot and Ankle Disability Index was used to assess functional limitation related to foot and ankle disorders. It includes items related to pain and activities of daily living and provides a clinically meaningful estimate of disability in individuals with ankle problems (17). The Y Balance Test was used to assess dynamic balance, lower limb control, and neuromuscular performance. Reach distance was assessed in the anterior, posteromedial, and posterolateral directions, and the composite score was calculated to represent overall dynamic balance performance (18,19). Data were analyzed using SPSS version 27.0. Continuous variables were presented as mean and standard deviation, while categorical variables were reported as frequency and percentage. The normality of continuous data was assessed using the Kolmogorov-Smirnov test. As the data were normally distributed, parametric tests were applied. Independent sample t-test was used to compare baseline and post-treatment differences between the two groups, while paired sample t-test was used to assess within-group changes from pre-treatment to post-treatment. A p-value of ≤0.05 was considered statistically significant. Effect size was reported using Cohen's d to estimate the magnitude of between-group differences.

RESULTS

A total of 66 participants completed the trial, with 33 participants in the sensor-based intelligent rehabilitation group and 33 participants in the proprioceptive neuromuscular facilitation group. No dropout was reported; therefore, all enrolled participants were included in the final analysis. The demographic characteristics were comparable between the two groups. The mean age was 28.15 ± 4.62 years in the sensor-based rehabilitation group and 26.64 ± 5.10 years in the PNF group, with no statistically significant difference between groups (p = 0.212). The mean height was 167.63 ± 9.02 cm in the sensor-based rehabilitation group and 169.12 ± 10.70 cm in the PNF group, which was also statistically comparable (p = 0.543). Based on the corrected values reported in the demographic table, the mean weight was 60.82 ± 9.95 kg in the sensor-based rehabilitation group and 59.66 ± 9.11 kg in the PNF group, with no significant difference between groups (p = 0.623). Gender distribution was also similar between groups. In the sensor-based rehabilitation group, 12 participants were male (36.4%) and 21 were female (63.6%), while in the PNF group, 11 participants were male (33.3%) and 22 were female (66.7%). The difference in gender distribution was not statistically significant (p = 0.796). Regarding the affected side, 13 participants (39.4%) in the sensor-based rehabilitation group had right-sided involvement and 20 participants (60.6%) had left-sided involvement. In the PNF group, 17 participants (51.5%) had right-sided involvement and 16 participants (48.5%) had left-sided involvement. The distribution of the affected side was not significantly different between groups (p = 0.323). These findings indicated acceptable baseline comparability between the two groups before intervention.

At baseline, the Visual Analogue Scale score was 7.21 ± 1.34 in the sensor-based rehabilitation group and 6.76 ± 1.37 in the PNF group. The baseline between-group difference was not statistically significant, with a mean difference of 0.45, 95% CI -0.22 to 1.12, p = 0.182, and Cohen's d = 0.33. After treatment, the VAS score decreased to 3.60 ± 1.60 in the sensor-based rehabilitation group and 4.45 ± 1.42 in the PNF group. The post-treatment difference was statistically significant, with a mean difference of -0.85, 95% CI -1.59 to -0.11, p = 0.026, and Cohen's d = -0.56. Functional ability measured through the Foot and Ankle Disability Index was comparable before treatment. The pre-treatment FADI score was 50.79 ± 7.83 in the sensor-based rehabilitation group and 49.36 ± 7.27 in the PNF group, with a mean difference of 1.43, 95% CI -2.29 to 5.15, p = 0.445, and Cohen's d = 0.19. After treatment, the FADI score increased to 65.88 ± 7.27 in the sensor-based rehabilitation group and 62.00 ± 5.79 in the PNF group. The post-treatment difference was statistically significant, with a mean difference of 3.88, 95% CI 0.64 to 7.12, p = 0.020, and Cohen's d = 0.59.

Dynamic balance measured through the Y Balance Test showed almost identical baseline scores in both groups. The pre-treatment Y Balance Test score was 69.54 ± 3.27 in the sensor-based rehabilitation group and 69.57 ± 3.35 in the PNF group, with a mean difference of -0.03, 95% CI -1.66 to 1.60, p = 0.971, and Cohen's d = -0.01. After treatment, the Y Balance Test score improved to 79.66 ± 3.54 in the sensor-based rehabilitation group and 76.93 ± 3.70 in the PNF group. The post-treatment difference was statistically significant, with a mean difference of 2.73, 95% CI 0.95 to 4.51, p = 0.003, and Cohen's d = 0.75. The mean change analysis showed that pain intensity decreased by 3.61 points in the sensor-based rehabilitation group and 2.31 points in the PNF group. The FADI score improved by 15.09 points in the sensor-based rehabilitation group and 12.64 points in the PNF group. Similarly, the Y Balance Test score improved by 10.12 points in the sensor-based rehabilitation group and 7.36 points in the PNF group. These values showed greater numerical improvement in the sensor-based intelligent rehabilitation group across all measured clinical outcomes.

The Cumberland Ankle Instability Tool was mentioned in the methodology as part of participant eligibility and screening. However, CAIT scores were not reported in the available results; therefore, it was treated as a screening tool rather than a final outcome measure in this revised results section. Exact within-group paired t-test values could not be calculated from the available summary data because paired analysis requires either raw pre-treatment and post-treatment participant-level data or the mean and standard deviation of within-participant change scores. Therefore, mean change values were added, but exact paired t and p-values should be inserted after analysis of the original dataset.

Table 1: Baseline demographic comparability

Variable	Group A: Sensor-based rehabilitation	Group B: PNF	Test used	p-value
Age, years	28.15 ± 4.62	26.64 ± 5.10	Independent t-test	0.212
Height, cm	167.63 ± 9.02	169.12 ± 10.70		0.543

Weight, kg	60.82 ± 9.95	59.66 ± 9.11		0.623
Male/Female	12/21	11/22	Chi-square test	0.796
Right/Left affected side	13/20	17/16		0.323

Table 2: Corrected between-group outcome analysis

Outcome	Time point	Group A: Sensor-based rehabilitation	Group B: PNF	Mean difference	95% CI	p-value	Cohen’s d
VAS	Pre-treatment	7.21 ± 1.34	6.76 ± 1.37	0.45	-0.22 to 1.12	0.182	0.33
	Post-treatment	3.60 ± 1.60	4.45 ± 1.42	-0.85	-1.59 to -0.11	0.026	-0.56
FADI	Pre-treatment	50.79 ± 7.83	49.36 ± 7.27	1.43	-2.29 to 5.15	0.445	0.19
	Post-treatment	65.88 ± 7.27	62.00 ± 5.79	3.88	0.64 to 7.12	0.020	0.59
Y Balance Test	Pre-treatment	69.54 ± 3.27	69.57 ± 3.35	-0.03	-1.66 to 1.60	0.971	-0.01
	Post-treatment	79.66 ± 3.54	76.93 ± 3.70	2.73	0.95 to 4.51	0.003	0.75

Table 3: Mean change data

Outcome	Direction of improvement	Group A change	Group B change	Difference in improvement
VAS	Reduction	3.61-point reduction	2.31-point reduction	1.30 greater reduction in Group A
FADI	Increase	15.09-point increase	12.64-point increase	2.45 greater increase in Group A
Y Balance Test	Increase	10.12-point increase	7.36-point increase	2.76 greater increase in Group A

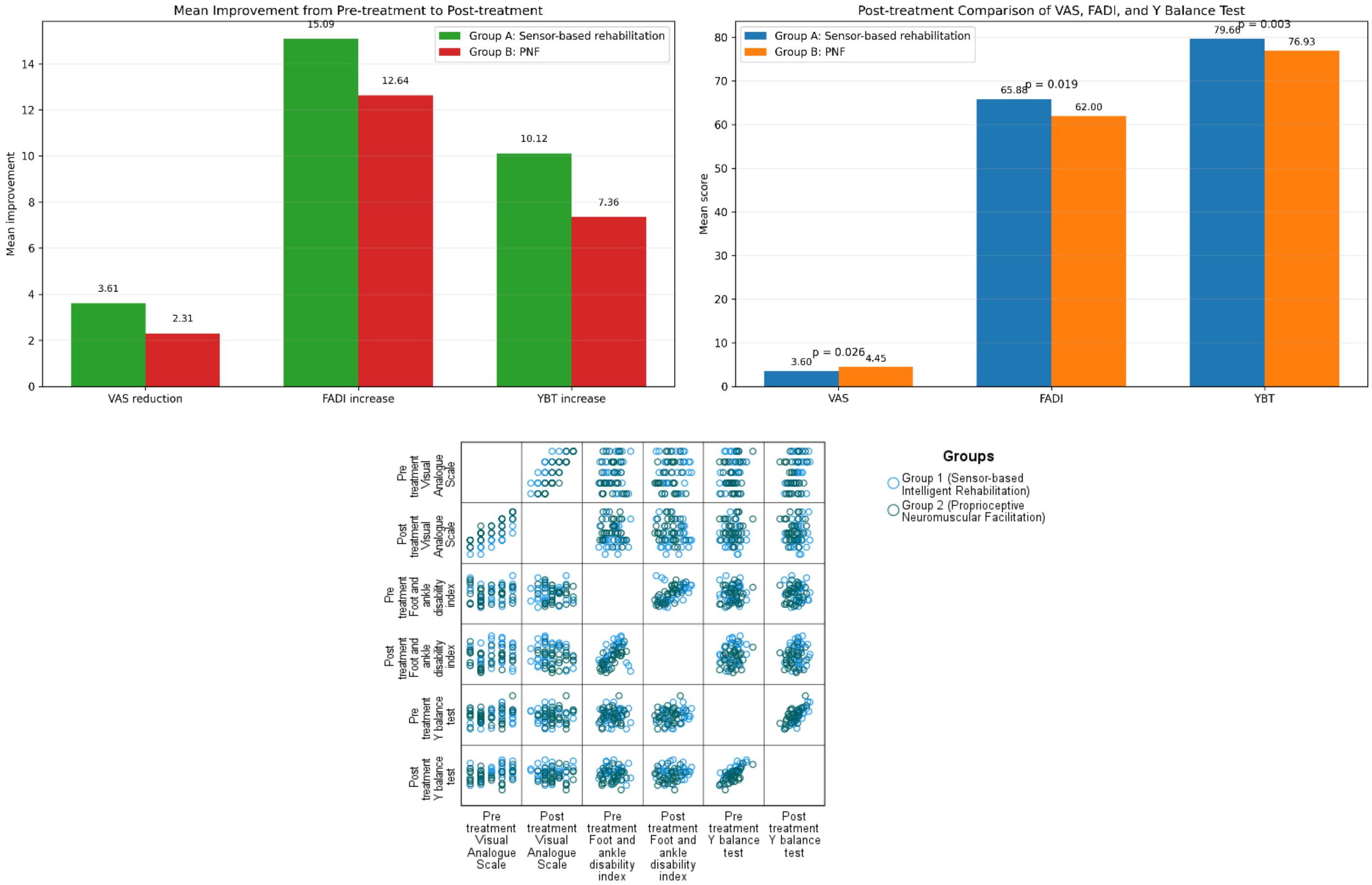

Figure 1. Pre- and post-treatment comparisons of VAS, FADI, and Y Balance Test

DISCUSSION

This study compared sensor-based intelligent rehabilitation with proprioceptive neuromuscular facilitation in adults with functional ankle instability and showed that both interventions produced improvement in pain, functional ability, and dynamic balance. However, the sensor-based rehabilitation group demonstrated greater post-treatment improvement than the PNF group. Pain intensity was lower after treatment in the sensor-based rehabilitation group, while functional ability and Y Balance Test scores were higher. These findings suggested that real-time sensor-guided rehabilitation may offer additional clinical benefit over therapist-guided PNF alone, particularly when the aim is to improve dynamic control and functional performance in patients with functional ankle instability. The greater improvement observed in the sensor-based rehabilitation group may be explained by the continuous feedback provided during exercise performance. Functional ankle instability is closely related to impaired proprioception, delayed muscular response, poor postural control, and repeated episodes of giving way. Sensor-based systems allow patients to see or receive immediate information about plantar pressure distribution, weight shifting, balance errors, and movement control. This feedback may improve motor learning by helping patients recognize faulty movement patterns and correct them during the same session. In contrast, PNF relies mainly on therapist-applied resistance, verbal cues, and manual facilitation. Although PNF is clinically useful for improving neuromuscular control, the feedback may be less continuous and less objectively measurable than that provided through wearable sensor systems.

The findings of the present study were consistent with previous literature supporting the role of sensor-based technology in ankle assessment and rehabilitation. One previous study reported that smart insoles were useful in assessing dynamic stability among individuals with chronic ankle instability, supporting the value of sensor-based systems in identifying balance and movement deficits (20). Another study used shoe-integrated sensors for the diagnosis of associated syndesmotic injury in chronic lateral ankle instability and demonstrated the potential of wearable technology in objective ankle evaluation (21). Although these studies mainly focused on assessment and diagnosis rather than treatment, they supported the concept that sensor-based systems can provide useful biomechanical and functional information in ankle instability. The present study extended this concept by using sensor feedback as an active rehabilitation tool and showed measurable improvement in pain, disability, and dynamic balance. The current findings also aligned with biomechanical evidence showing that individuals with functional ankle instability present with altered gait patterns, impaired loading strategies, and reduced dynamic control. A previous study based on three-dimensional motion analysis reported clear biomechanical differences in individuals with functional ankle instability, highlighting the need for rehabilitation approaches that address movement quality and functional control rather than pain alone (22). The present study supported this view because improvement was observed not only in pain intensity but also in FADI and Y Balance Test scores. This suggested that sensor-based rehabilitation may be clinically useful because it targets both symptom reduction and movement correction during functional tasks.

Evidence from wearable sensor research in other lower-limb rehabilitation areas also supported the broader clinical potential of sensor-guided systems. One study using wearable sensors and machine learning for intelligent ankle-foot prosthetic control showed that sensor-derived information could assist in recognizing movement intention and improving adaptive lower-limb function (23). Although that study involved prosthetic users rather than individuals with functional ankle instability, it provided indirect support for the role of wearable systems in improving movement monitoring and functional decision-making. The present trial applied this principle in a rehabilitation setting, where real-time feedback was used to guide exercise performance and improve clinical outcomes. The improvement observed in the PNF group was also clinically meaningful and supported the continued role of therapist-guided neuromuscular rehabilitation in ankle conditions. A previous study reported that massage combined with PNF improved ankle range of motion after ankle injury, suggesting that PNF may support restoration of mobility and neuromuscular control (24). The present study added to this evidence by showing that PNF was associated with improvement in pain, disability, and balance. However, the greater improvement in the sensor-based group indicated that real-time feedback and objective monitoring may enhance rehabilitation effects beyond conventional facilitation techniques alone. This does not reduce the clinical value of PNF, but it suggests that sensor-based methods may be especially useful when dynamic balance, movement accuracy, and patient engagement are important therapeutic goals.

The findings were also supported by literature on intelligent rehabilitation devices for ankle recovery. A previous study developed and validated a wearable telerehabilitation device for postoperative rehabilitation in chronic ankle instability and emphasized the value of portable sensor systems for monitoring gait and biomechanical performance (25). The present study differed because it focused on non-operative functional ankle instability and used sensor feedback during supervised rehabilitation rather than postoperative monitoring. Even with this difference, both studies supported the growing relevance of wearable sensor technology in ankle rehabilitation. The combined evidence suggested that sensor-based systems may help make rehabilitation more objective, interactive, and individualized. The clinical implication of these findings was that sensor-based intelligent rehabilitation may be considered as a useful option for patients with functional ankle instability, especially where the goal is to improve balance, functional performance, and movement confidence. Its ability to provide immediate feedback may help patients understand their movement errors more clearly and may support better adherence to corrective exercise patterns. In clinical practice, this approach may complement rather than completely replace traditional physiotherapy. Therapist supervision remains important for exercise selection, safety monitoring, progression, and clinical decision-making, while sensor systems may add objective performance tracking and enhance patient engagement.

A strength of this study was its randomized controlled design with equal group allocation and the use of clinically relevant outcome measures, including VAS, FADI, and Y Balance Test. These tools allowed assessment of pain, disability, and dynamic balance, which are important domains in functional ankle instability. Another strength was the direct comparison of sensor-based intelligent rehabilitation with PNF, as head-to-head comparisons between technology-assisted rehabilitation and conventional neuromuscular facilitation remain limited. The use of a practical clinical setting also increased the applied value of the findings. However, several limitations should be considered while interpreting the results. The study was conducted at a single center with a relatively small sample size, which may limit generalizability. The follow-up period was short, and long-term retention of treatment effects was not assessed. Participant blinding was not practically possible because the two interventions were visibly different, although assessor blinding could reduce measurement bias. The study also did not report adherence, adverse events, treatment satisfaction, or detailed dropout monitoring, which are important elements in randomized controlled trials. In addition, the Cumberland Ankle Instability Tool was mentioned in the methodology, but its results were not reported as an outcome; therefore, its role should be clearly limited to screening unless pre- and post-treatment CAIT data are added. Cost, availability of smart insole systems, training of clinicians, sensor placement issues, internet instability, and load shedding may also affect the feasibility of sensor-based rehabilitation in routine clinical environments.

Future studies should include larger multicenter samples, longer follow-up periods, and more detailed reporting of adherence, adverse events, and patient satisfaction. Further research should also compare sensor-based rehabilitation alone, PNF alone, and combined sensor-based rehabilitation with PNF to determine whether an integrated protocol produces superior outcomes. The inclusion of cost-effectiveness analysis, home-based monitoring, return-to-activity outcomes, recurrence of ankle sprain, and standardized CAIT scoring would strengthen future evidence. Overall, the present findings suggested that sensor-based intelligent rehabilitation produced greater short-term improvements in pain, functional disability, and dynamic balance than PNF in adults with functional ankle instability, but further high-quality trials are needed before broad clinical recommendations can be made.

CONCLUSION

This study concluded that both sensor-based intelligent rehabilitation and proprioceptive neuromuscular facilitation were beneficial for improving pain, functional ability, and dynamic balance in individuals with functional ankle instability. However, sensor-based intelligent rehabilitation showed comparatively greater clinical benefit, suggesting that real-time feedback and objective movement correction may enhance rehabilitation outcomes beyond conventional facilitation techniques alone. These findings support the practical use of sensor-assisted rehabilitation as an effective and patient-centered approach for improving ankle stability and functional recovery.

AUTHOR CONTRIBUTION

Author	**Contribution**
Dr. Arooj Rani	Conceptualization, Methodology, Formal Analysis, Writing - Original Draft, Validation, Supervision
Dr. Zohaib Rana	Methodology, Investigation, Data Curation, Writing - Review & Editing
Dr. Zainab Fareed	Investigation, Data Curation, Formal Analysis, Software
Dr. Ayesha Fareed	Software, Validation, Writing - Original Draft
Dr. Amina Kainat	Formal Analysis, Writing - Review & Editing
Dr. Maiza Malik Mustafa	Writing - Review & Editing, Assistance with Data Curation

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