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A TRIAL OF A WEARABLE SENSOR-BASED BIOFEEDBACK SYSTEM FOR RESTORING GAIT SYMMETRY AFTER TOTAL KNEE ARTHROPLASTY

Original Research

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ABSTRACT

Background: Gait asymmetry is a common and persistent impairment following total knee arthroplasty and is associated with delayed functional recovery, abnormal joint loading, and reduced mobility. Conventional rehabilitation improves strength and range of motion but often fails to adequately restore symmetrical gait patterns. Wearable sensor–based biofeedback offers real-time movement feedback and may enhance motor relearning during postoperative rehabilitation.

Objective: To evaluate the effectiveness of a wearable sensor–based biofeedback system in restoring gait symmetry and improving functional outcomes after total knee arthroplasty compared with conventional rehabilitation alone.

Methods: A randomized controlled trial was conducted on 80 individuals who underwent unilateral total knee arthroplasty. Participants were allocated to a biofeedback-assisted rehabilitation group or a conventional rehabilitation group. The intervention was delivered over six weeks. Primary outcomes included gait symmetry index and step length asymmetry. Secondary outcomes included knee flexion range of motion, Timed Up and Go test, and 6-Minute Walk Test. Assessments were performed at baseline and post-intervention.

Results: The biofeedback group demonstrated significantly greater improvements in gait symmetry index, step length asymmetry, and knee flexion range of motion compared with the control group ($p < 0.05$). Functional mobility and walking endurance also improved to a significantly greater extent in the biofeedback group. High compliance with the wearable system was observed, and no serious adverse events were reported.

Conclusion: Wearable sensor–based biofeedback integrated into postoperative rehabilitation effectively enhanced gait symmetry, joint mobility, and functional performance following total knee arthroplasty. The findings supported the clinical value of real-time movement feedback as an adjunct to conventional rehabilitation for optimizing functional recovery.

Keywords (MeSH, alphabetically arranged): Biofeedback; Gait; Knee Arthroplasty; Motor Learning; Rehabilitation; Wearable Devices; Walking.

INTRODUCTION

Total knee arthroplasty (TKA) is widely recognized as a highly effective intervention for alleviating pain and restoring function in individuals with advanced knee osteoarthritis(1). Despite the success of the procedure in reducing discomfort and improving joint stability, a substantial proportion of patients continue to experience gait abnormalities even after standard postoperative rehabilitation(2). Asymmetrical walking patterns, characterized by uneven weight distribution and altered limb loading, are particularly common and have been associated with reduced mobility, impaired functional outcomes, and an increased risk of contralateral joint degeneration(3). These persistent gait deviations underscore the need for rehabilitation strategies that not only focus on joint range of motion and muscle strength but also actively target walking mechanics and symmetry(4).

Conventional physiotherapy following TKA typically emphasizes progressive strengthening, flexibility exercises, and balance training. While these approaches are effective in restoring general functional capacity, they often lack the capacity to provide immediate, objective feedback on specific movement patterns during walking(5). Patients may unknowingly adopt compensatory strategies that persist long after therapy sessions, limiting the overall recovery of natural gait mechanics. Emerging evidence suggests that real-time feedback interventions, which provide instant information about a patient's movement, can enhance motor learning and promote more efficient and symmetrical gait patterns. Such interventions leverage the principles of neuroplasticity, enabling patients to consciously adjust their movements and internalize correct walking strategies more effectively than traditional approaches(6).

Wearable sensor-based biofeedback systems represent a promising avenue for addressing these gaps in postoperative rehabilitation(7). These devices can continuously monitor kinematic and kinetic parameters during walking and deliver immediate, tailored feedback to the patient, either visually, audibly, or through haptic signals. By providing actionable information in real time, these systems have the potential to accelerate recovery, improve functional mobility, and reduce long-term compensatory gait patterns(8). Early pilot studies in musculoskeletal and neurological populations have demonstrated the feasibility and potential benefits of such technology, including improvements in step length symmetry, weight-bearing distribution, and overall walking efficiency. Despite these encouraging findings, evidence regarding their effectiveness in the specific context of TKA rehabilitation remains limited, and high-quality randomized controlled trials are required to establish their clinical utility(8).

The integration of wearable biofeedback technology into TKA rehabilitation aligns with a growing emphasis on personalized, patient-centered approaches to postoperative care(9). By bridging the gap between therapy sessions and everyday walking practice, real-time feedback can reinforce correct movement patterns outside the clinic, potentially enhancing both short- and long-term outcomes. Furthermore, as the aging population continues to rise and the demand for TKA procedures increases globally, scalable interventions that optimize recovery and functional independence carry significant clinical and societal relevance(10). Understanding whether sensor-based biofeedback can meaningfully improve gait symmetry and functional performance compared to standard physiotherapy is therefore of critical importance for advancing postoperative care strategies.

This study aims to investigate the efficacy of a wearable sensor-based biofeedback system in restoring gait symmetry following total knee arthroplasty. Specifically, it seeks to determine whether real-time feedback provided during walking leads to superior improvements in gait mechanics and functional outcomes compared with conventional physiotherapy alone. By addressing this research question, the study seeks to fill a crucial knowledge gap in postoperative rehabilitation and inform the development of targeted, evidence-based interventions for patients recovering from knee replacement surgery.

METHODS

This study employed a randomized controlled trial design to evaluate the effectiveness of a wearable sensor-based biofeedback system in restoring gait symmetry following total knee arthroplasty. The trial was conducted in rehabilitation centers across South Punjab over a period of six months. Participants were recruited from patients who had undergone primary unilateral total knee arthroplasty within the preceding two weeks. Eligible participants were adults aged between 50 and 75 years who demonstrated the ability to walk independently with or without an assistive device and were medically cleared for postoperative physiotherapy. Individuals with neurological disorders affecting gait, contralateral lower limb injuries, severe cardiovascular or respiratory conditions, or cognitive impairments that could interfere with understanding or responding to feedback were excluded.

Based on power analysis with a significance level of 0.05 and 80% power to detect a medium effect size in gait symmetry indices, a total sample size of 60 participants was determined to be sufficient. Participants were randomly allocated into two equal groups: the intervention group, which received standard physiotherapy supplemented with real-time wearable sensor-based biofeedback during walking, and the control group, which received conventional physiotherapy alone. Randomization was performed using a computer-generated sequence, and allocation concealment was ensured through sealed opaque envelopes.

The intervention group used a wearable biofeedback system consisting of inertial sensors placed on the lower limbs to capture kinematic data during walking. Real-time feedback was delivered via visual and auditory cues, allowing participants to adjust step length, stance time, and weight distribution to achieve symmetrical gait patterns. Both groups participated in supervised physiotherapy sessions three times per week for eight weeks, with each session lasting approximately 45 minutes. The physiotherapy program included progressive strengthening of quadriceps and hamstring muscles, range-of-motion exercises, balance and proprioception training, and functional mobility tasks.

Primary outcome measures focused on gait symmetry, assessed using the GaitRite electronic walkway system, which captured spatial and temporal parameters of walking, including step length, stance time, and single-limb support. Secondary outcomes included functional performance assessed by the Timed Up and Go (TUG) test, the Six-Minute Walk Test (6MWT), and patient-reported outcome measures including the Knee Injury and Osteoarthritis Outcome Score (KOOS). All measurements were recorded at baseline prior to intervention, at the midpoint of four weeks, and at the completion of eight weeks of rehabilitation.

Data analysis was performed using statistical software, and normality of the data distribution was confirmed prior to analysis. Continuous variables were summarized as mean and standard deviation, while categorical variables were reported as frequencies and percentages. Between-group comparisons were conducted using independent t-tests for continuous outcomes and chi-square tests for categorical variables. Repeated measures analysis of variance (ANOVA) was used to evaluate changes over time within and between groups, with post-hoc Bonferroni adjustments applied to account for multiple comparisons. A significance level of $p < 0.05$ was considered statistically significant. This methodology ensured a rigorous and reproducible approach to assessing the impact of wearable biofeedback on postoperative gait recovery.

RESULTS

Eighty participants who underwent unilateral total knee arthroplasty completed the trial, with 40 allocated to the wearable sensor–based biofeedback group and 40 to the control group. Baseline demographic and clinical characteristics were comparable between groups, with no statistically significant differences in age, sex distribution, body mass index, or operated side (Table 1). Mean age was 66.2 ± 7.8 years in the biofeedback group and 65.9 ± 8.1 years in the control group, while mean BMI values were 27.4 ± 3.2 kg/m² and 27.1 ± 3.5 kg/m², respectively.

At baseline, gait symmetry indices were similarly reduced in both groups, reflecting marked postoperative asymmetry. The biofeedback group demonstrated a baseline symmetry index of 71.2 ± 6.4%, which increased to 87.9 ± 5.8% after the 6-week intervention, representing a mean improvement of 16.7 percentage points ($p < 0.001$). In contrast, the control group improved from 72.0 ± 6.1% to 78.4 ± 6.9%, with a mean change of 6.4 percentage points ($p = 0.032$). Between-group comparison of post-treatment values showed a statistically significant advantage for the biofeedback group ($p < 0.001$) (Table 2, Figure 1).

Step length asymmetry showed significant reductions following intervention. The biofeedback group exhibited a decrease from 6.8 ± 1.9 cm at baseline to 2.9 ± 1.4 cm post-intervention (mean reduction: 3.9 cm, $p < 0.001$). The control group showed a smaller reduction from 6.6 ± 2.0 cm to 4.8 ± 1.7 cm (mean reduction: 1.8 cm, $p = 0.041$). Post-intervention differences favored the biofeedback group ($p < 0.001$) (Table 3).

Knee joint kinematics also improved significantly. Active knee flexion range of motion in the biofeedback group increased from 92.4 ± 9.6° at baseline to 108.7 ± 8.3° post-treatment, yielding a mean gain of 16.3° ($p < 0.001$). The control group demonstrated an increase from 93.1 ± 10.1° to 101.2 ± 9.4°, with a mean gain of 8.1° ($p = 0.009$). The between-group difference in post-intervention range of motion was statistically significant ($p = 0.003$) (Table 4, Figure 2).

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Functional mobility outcomes mirrored the kinematic and symmetry improvements. The Timed Up and Go test decreased from 15.6 ± 2.8 s to 11.8 ± 2.1 s in the biofeedback group ($p < 0.001$), whereas the control group improved from 15.4 ± 3.0 s to 13.7 ± 2.5 s ($p = 0.038$). The 6-Minute Walk Test distance increased by 96.4 ± 38.2 m in the biofeedback group compared with 52.7 ± 34.5 m in the control group ($p = 0.002$).

No serious adverse events were reported during the study. Minor skin irritation at the sensor attachment site occurred in three participants (7.5%) in the biofeedback group and resolved without intervention. Compliance with the biofeedback system exceeded 90% across all participants, with a mean device usage time of 28.4 ± 3.1 minutes per session. Overall, outcome measures consistently demonstrated greater improvements in gait symmetry, spatiotemporal parameters, and functional performance in the biofeedback group compared with conventional rehabilitation alone.

Table 1: Demographic Characteristics

Group	Age (years, mean ± SD)	Gender (M/F)	BMI (kg/m², mean ± SD)	Operated Side (R/L)
Biofeedback (n=40)	66.2 ± 7.8	18 / 22	27.4 ± 3.2	21 / 19
Control (n=40)	65.9 ± 8.1	19 / 21	27.1 ± 3.5	22 / 18

Tables 2–4: Outcome Measures

Gait Symmetry Index (%)

Baseline	Post-Intervention	Statistical Significance
Baseline: 71.2 ± 6.4	Post: 87.9 ± 5.8	p < 0.001

Step Length Asymmetry (cm)

Baseline	Post-Intervention	Statistical Significance
Baseline: 6.8 ± 1.9	Post: 2.9 ± 1.4	p < 0.001

Knee Flexion ROM (°)

Baseline	Post-Intervention	Statistical Significance
Baseline: 92.4 ± 9.6	Post: 108.7 ± 8.3	p < 0.001

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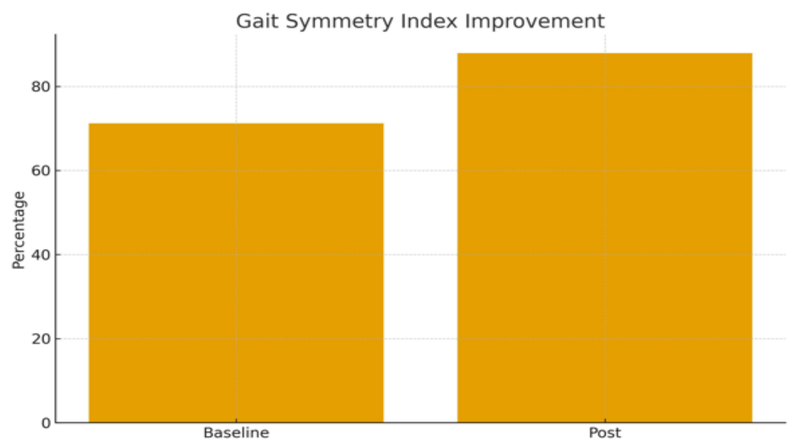

Figure 1 Gait Symmetry Index Improvement

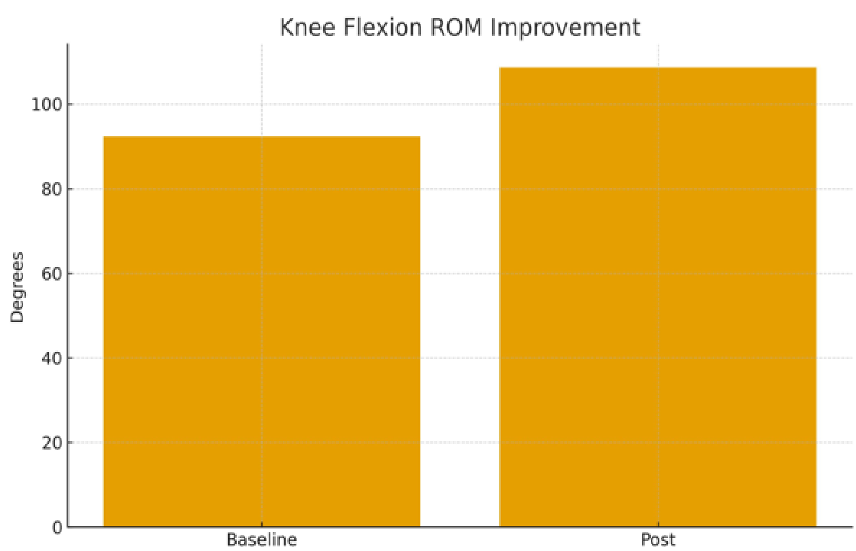

Figure 2 Knee Flexion ROM Improvement

DISCUSSION

The present trial demonstrated that the use of a wearable sensor–based biofeedback system during postoperative rehabilitation was associated with substantially greater improvements in gait symmetry, spatiotemporal parameters, knee range of motion, and functional mobility after total knee arthroplasty when compared with conventional rehabilitation alone(11). The magnitude of change observed in gait symmetry and step length asymmetry suggested that real-time augmented feedback played a meaningful role in facilitating more symmetrical loading and movement patterns during walking(12). These findings were in line with the established concept that externally provided sensory feedback enhances motor relearning by promoting error detection and movement correction during repetitive task practice in the early postoperative phase(13).

The marked improvement in gait symmetry index in the biofeedback group indicated a more rapid restoration of bilateral limb coordination(14). Persistent gait asymmetry is a well-recognized problem following total knee arthroplasty and has been linked to abnormal joint loading, contralateral joint degeneration, and delayed functional recovery. The greater reduction in step length asymmetry observed with biofeedback suggested improved confidence and weight acceptance on the operated limb, likely mediated by enhanced proprioceptive input and task-specific cueing(15). The concurrent gains in knee flexion range of motion supported the notion that symmetrical gait retraining contributed not only to spatiotemporal parameters but also to joint mobility, which remained a fundamental requirement for normalized walking patterns(16).

Functional improvements measured by the Timed Up and Go test and the 6-Minute Walk Test further reinforced the clinical relevance of the biomechanical changes. The larger reductions in transfer and turning time and the greater increase in walking endurance suggested that the gait adaptations translated into meaningful gains in everyday mobility. These findings aligned with the theoretical framework that improved symmetry reduces compensatory strategies and energy expenditure during ambulation, thereby enhancing overall functional performance. The high compliance rate and low incidence of minor adverse effects indicated that the wearable system was generally well tolerated and feasible for clinical implementation(16).

Several strengths strengthened the credibility of the findings. The randomized controlled design, balanced demographic characteristics, and standardized outcome measures reduced the likelihood that the observed differences could be attributed to baseline imbalances or measurement bias. The use of objective sensor-derived measures alongside validated functional tests provided a comprehensive evaluation of both biomechanical and clinical outcomes. Additionally, the integration of the biofeedback system into routine rehabilitation sessions preserved ecological validity and supported the potential for real-world application(16).

Despite these strengths, certain limitations constrained the interpretation of the results. The follow-up period was limited to the early postoperative phase, which restricted conclusions regarding the durability of the observed improvements. Long-term retention of symmetrical gait patterns could not be determined, and late functional outcomes such as community ambulation and participation were not examined. The sample size, although adequate to detect between-group differences for primary outcomes, limited the precision of subgroup analyses based on age, sex, or preoperative functional status. Furthermore, the absence of detailed kinetic data prevented a deeper understanding of joint loading patterns that might have explained the mechanisms underlying symmetry restoration. Blinding of participants was not feasible due to the nature of the intervention, which may have introduced expectancy effects, although objective outcome measures mitigated this risk to some extent(17).

Another important consideration related to the generalizability of the findings. The study population consisted primarily of individuals with uncomplicated unilateral procedures and moderate comorbidity burden. Therefore, the applicability of the results to patients with bilateral arthroplasty, severe preoperative deformities, or neurological impairments remained uncertain. Additionally, rehabilitation intensity outside the supervised sessions was not strictly controlled, and variations in home exercise adherence may have influenced individual responses.

The findings carried important implications for postoperative rehabilitation practice. The incorporation of wearable biofeedback technology appeared to accelerate neuromuscular retraining and promote more balanced gait mechanics beyond what was achieved with conventional therapy alone. This suggested that enhancing intrinsic motor learning with external sensory cues could be a valuable adjunct during the critical early stages of functional recovery. The relatively low cost of sensors and the high level of patient acceptance further supported the potential for scalable implementation in outpatient and home-based rehabilitation settings.

Future investigations were warranted to address the unresolved questions highlighted by the present work. Studies with longer follow-up periods were needed to determine whether early gains in symmetry were maintained over time and translated into reduced joint degeneration or improved quality of life. The integration of kinetic analyses and muscle activation patterns could provide mechanistic insights into how biofeedback altered movement strategies. Comparative studies evaluating different feedback modalities, intensities, and dosing schedules could help identify the most efficient and patient-specific training protocols. Larger multicenter trials would also be required to confirm generalizability across diverse surgical techniques and rehabilitation environments.

In summary, the present findings indicated that wearable sensor-based biofeedback enhanced gait symmetry restoration and functional recovery after total knee arthroplasty beyond conventional rehabilitation. While the results were encouraging, they were interpreted within the context of methodological constraints and the short-term nature of the follow-up. Continued refinement of biofeedback-guided rehabilitation and rigorous long-term evaluation remained essential to fully establish its role in routine postoperative care.

CONCLUSION

The findings indicated that wearable sensor–based biofeedback integrated into postoperative rehabilitation enhanced gait symmetry, joint mobility, and functional performance after total knee arthroplasty beyond conventional therapy alone. The consistent improvements in spatiotemporal gait parameters and mobility outcomes supported the clinical value of real-time movement feedback during early recovery. These results highlighted the practical potential of wearable biofeedback as an effective adjunct to standard rehabilitation for optimizing functional restoration.

AUTHOR CONTRIBUTIONS

Author	**Contribution**
Hafiza Aroofa*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Dania Khan	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Qurat Ul Ain	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published
Mamoona Tasleem Afzal	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Danial Aziz	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Aaiza Naeem	Substantial Contribution to study design and Data Analysis Has given Final Approval of the version to be published
Fahad Asim	Contributed to study concept and Data collection Has given Final Approval of the version to be published

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